

final report

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Alternative Options to Power Captive Bolts Devices for Cattle

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Executive summary

Gunpowder-powered captive bolts for humane slaughter may be problematic in some countries where gun laws limit access to gunpowder charges. An alternative power source for portable, handheld and single-operator captive bolts suitable for use on large animals such as cattle may allow ongoing use of stunning in these markets if a low-cost alternative can be developed. Pneumatic power was identified as the most suitable and safest source of non-gunpowder power for captive bolt use in small abattoirs. Literature review clarified required performance specifications for a penetrative stunner for cattle. Pneumatic products developed for other applications currently achieved these thresholds. Key features of non-gunpowder devices were examined and features for a portable, hand-held device identified. Competing designs were developed, compared and evaluated in a series of desktop studies. An optimal configuration of compressed gas source, compression chamber, valve, trigger, bolt and bolt chamber assembly was identified.

A prototype device (T-Bolt20) incorporated key (and often bespoke) design features into a safetyfirst mechanism including priming switches, pressure gauges, pressure release valves and universal fill fittings. A number of safety features were incorporated. The bolt chamber included energyenhancing mechanisms that, when combined with the trigger and valve mechanism, ensured the bolt reached the required kinetic energy with the shortest bolt internal travel distance and lowest gas pressure. Compressed gas alternatives include CO2 and compressed air are available as bottled gas; the preferred commercial source. These supply cylinders decant to smaller portable cylinders used to charge the device. Bottled gas is a filtered, dry product, has mature third-party supply chains and is cheap. This discourages abattoirs from installing high-pressure compressors which bring inherent risks of compressor failure and use of non-filtered, humid air which over time may damage the unit. The device uses 14–20 grams of gas per discharge. A large gas supply cylinder (>20L) holds many thousand discharges. This system provides certainty of supply in most countries.

The T-Bolt20 was extensively tested against gunpowder-fired captive bolt devices using both a velocity test and penetration test. Once the design was finalised, this progressed to cadaver testing. The device performed consistently and effectively on cadavers. Animal ethics approval was obtained for field study use on ten cows destined for slaughter. A series of recognised tests for assessing stunning effectiveness (unconsciousness and death) combined with physical tests for length and direction of bolt penetration were used to assess the performance of the T-Bolt20. The device performed reliably and met minimum requirements of performance and was subsequently assessed as fit for purpose.

Three complete T-Bolt20 devices in custom carry cases with supplies of disposables (such a o-rings, gas fitting adapters, etc.), detailed assembly, maintenance and use manual were provided. Complete Computer Aided Design (CAD) plans to allow immediate toll manufacturing were provided. A field demonstration of the T-Bolt20 in market (Vietnam) was undertaken mid-July 2019. This identified the most suitable gas supply system and desired use in works. Recommendations for modifications were received and these are being incorporated into the market version along with a percussive bolt and head assembly for non-penetrative stunning. The device was well received by market.

The terms of reference were met in full for this project.

Table of contents

1	Bac	Background5					
2	Proj	Project objectives 5					
3	Met	Methodology					
	3.1	Summary of project methodology	6				
	3.2	Literature Review	7				
	3.2.	L Captive bolt applications	7				
	3.2.2	2 Captive bolt mechanism of action	8				
	3.2.3	3 Neurophysiology relevant to captive bolts	8				
	3.2.4	Existing captive bolt propulsion sources	9				
	3.2.	5 Review of devices currently used in Vietnam	9				
	3.2.	5 Factors affecting performance	10				
	3.2.	7 The central role of kinetic energy	10				
	3.2.3	3 Minimum performance standards required	10				
	3.3	Choosing an alternative power source	11				
	3.4	Prototype design	12				
	3.4.	L Key features	12				
	3.4.2	2 Captive bolt assembly (front-end)	13				
	3.4.3	Pneumatic power unit assembly (compression chamber; back-end)	13				
	3.4.4	Computer Aided Design (CAD) plans	14				
	3.4.	5 Device operation - basic summary of procedures	15				
4	Res	ılts					
	4.1	Heading	18				
	4.1.	L Sub heading	18				
5	Discussion						
	5.1	Heading					
	5.1.	L Sub heading	18				
6	Con	clusions/recommendations	19				
	6.1	Heading	19				
	6.1.	L Sub heading	19				
7	Кеу	messages	19				
	7.1	Heading	19				

	7.1.1	Sub heading	19
8	Bibliogra	aphy	20
	8.1 Hea	ding	20
	8.1.1	Sub heading	20
9	Appendi	ix	20
	9.1 Hea	ding	20
	9.1.1	Sub heading	20

1 Background

Stunning via a captive bolt is recognised as an effective, safe and easily administered form of euthanasia or humane killing. For large animals (>5 kg), gunpowder-powered devices provide the most reliable, cost-effective, and portable captive bolt devices to the market and, as such, they are most often used to euthanise livestock outside of high-throughput commercial abattoirs. They are commonly carried and used by veterinarians, farmers and livestock attendants. The mandated use of captive bolts in small-scale abattoirs is an important components of the Export Supply Chain Assurance Scheme (ESCAS) requirements for the humane slaughter of Australian-derived livestock in importing countries. Portable, easy-to-use, reliable and cheap gunpowder-powered captive bolts have become the mainstay of slaughter stunning in the majority of importing countries receiving Australian livestock.

Public access to gunpowder-powered devices is problematic in some countries due to restrictions on access to gunpowder charges. Some countries have legislation that limits access to gunpowder products and gun-like devices to organisations such as the military and police. Alternative power sources are currently used in some captive bolts: springs, propane combustion, and compressed gas (pneumatics) Pneumatic captive bolts exist and are commonly in use, but almost predominantly on an industrial scale in larger abattoirs as fixed-in-place devices in developed countries. They are large, fixed-in-place, use piped gas for power and are supported by frames to allow the device to be handled by a single operator. These devices do not provide a suitable substitute for a small, portable, single-shot, gunpowder-powered captive bolt.

This project designed, developed and built a portable, hand-held, non-gunpowder-powered, easily maintained, cheap and reliable penetrative captive bolt that was able to perform to international stunning standards in a form that was suitable for use in small abattoirs.

2 Project objectives

This project had the following objectives:

- 1. A report summarising the current animal welfare standards required for humane cattle stunning devices.
- 2. A report summarising the alternative (non-gunpowder) power sources currently used for captive bolts and a review of alternative power technologies that may be used as replacement for gunpowder.
- 3. A report outlining the design, construction, and bench-top testing results of prototype captive bolts and an assessment of suitability for commercial manufacture and use. The objective of the report will be to inform the selection of the design or designs for commercial manufacture and identify manufacturing processes required (Go-No Go point).
- 4. A report of the field trials evaluating the selected prototype(s) performance as a captive bolt using:
 - a. post-mortem evidence using cattle cadavers, and

- ante-mortem evidence using live cattle, in a controlled Australian abattoir field trial. Field-test results would be compared to required animal welfare standards and desired technical specifications. The report will document the assessment of device performance against: animal welfare requirements, practical use specifications, safety (human and animal) and suitability for commercial manufacture (Go-No Go point).
- 5. A design and manufacturing plan for the commercial production of captive bolts. This will include a description of the necessary registration and accreditation certification, packaging requirements and documentation.
- 6. An optional demonstration of the technologies to authorities in Vietnam.

3 Methodology

3.1 Summary of project methodology

Literature review indicated that pneumatic power was currently the most suitable and safest alternative power source for a portable captive bolt.

Desktop research revealed that at least two USA-made portable pneumatic devices had recently entered the market: one was a non-penetrative model designed for salmon (Zephyr-F from Bock Industries) and the other was a penetrative model designed for cattle (Tomahawk DT from Nova Pneumatics). The Zephyr-F did not meet the technical specifications required for a cattle device, but the Tomahawk DT apparently did. Two Tomahawk DT devices were subsequently purchased and sent for bench and cadaver testing. Whilst the Tomahawk DT device was found to provide the necessary energy at full extension of the bolt to meet requirements for humane cattle stunning, the design had at least one serious flaw. Insufficient buffer distance was provided before the bolt head protrudes from the device. This prevents the bolt from attaining sufficient velocity (and hence kinetic energy) after firing and before exiting the device foramen and this prevents humane stunning in larger animals. The Tomahawk DT is unable to be adjusted to provide sufficient ramping-up of bolt speed and energy before contacting the animals' head meaning the device does not provide enough energy to penetrate the skull. This presents two serious risks: one of unsatisfactory animal welfare and one of increased operator risk, due to enhanced recoil arising from non-penetration of the bolt into the animal's skull.

The development of a bespoke pneumatic captive bolt that meets international stunning standards was progressed. No restrictive patents, intellectual or commercial property that prevents the construction of a non-gunpowder-powered captive bolt in any alternative power modality was identified. An independent, hand-held pneumatic captive bolt prototype was designed, built and bench tested before sending for a cadaver study. Compressed gas was found to be sufficient to generate the required energy (after allowing for differences in bolt acceleration compared to a gunpowder-powered device). This required the design of a pneumatically-dedicated bolt system and chamber to ensure the bolt had time and travel distance to accelerate to the required velocity to ensure consistent performance.

The dedicated front-end was tested using a power unit provided by an alternative manufacturer and a power unit was constructed using off-the-shelf equipment and a small compressed gas reservoir to enable hand-held operation and independent manufacture. This has passed both bench testing and cadaver testing studies which clearly demonstrated proof of concept. Adequate kinetic energy was generated to provide a penetration force in the largest of cow heads to the level of the brain stem. The unit has been assessed using both power and kinetic energy calculations and cadaver studies and was assessed to be fit for purpose. Seven fresh adult dairy cow heads from fallen stock were obtained from the local knackery and used to assess the penetration capacity of the unit. The captive bolt passed through the skull and entered the brain for all cadaver tests and for all device operators.

A small-scale euthanasia study was designed, and the protocol submitted to and subsequently approved by the Wildlife and Small Institutions Animal Ethics Committee (WSIAEC) of Agriculture Victoria (approval WSAIEC 15.18). A local (Victorian) study site (Glen Alvie) and suitable study cattle were identified for live animal testing. Ten cattle of varying breeds (Friesian, Jersey crossbreeds), ages (18 months to 7 years), sexes (cows and steers) and weights (300 to 675 kilograms) were processed. Nine of the ten animals were euthanised effectively (immediate and irreversible loss of consciousness) using the stunning device. The one animal that was not effectively stunned was investigated after death¹. The bolt was found at post mortem to have fully penetrated the skull but to have missed the brain, instead entering the left frontal sinus. This was as a result of malposition of the captive bolt at firing (user error) and not due to deviation of the bolt after firing or insufficient power (device failure).

A full set of computer-aided design (CAD) plans suitable for commissioning third-party manufacture along with three working prototypes were provided to MLA on completion of animal field trials. The CAD designs included computer graphics to depict the components and construction and technical and engineering information along with information on materials, processes, dimensions and tolerances to ensure manufacturing produces devices that meet required specifications. Three new devices were assembled and presented to MLA (with operations and maintenance manuals) for demonstrations in market as required.

3.2 Literature Review

A desktop review was performed to identify power sources used for currently available cattle captive bolts and to define the standards required for any newly developed cattle captive bolt to be considered humane, safe, and practical for the operating environment.

3.2.1 Captive bolt applications

Captives bolts are devices used to facilitate humane physical (non-chemical) killing of animals. They rely on tethered ('captive') projectiles that are applied directly to animals' craniums (Daly *et al.* 1987). Captive bolts have been used in many animal species (especially livestock) and a large amount of practical experience and scientific research related to their use has been accumulated. When used

¹ This animal was dispatched within 20 seconds of the first (unsuccessful) stun using a back-up gunpowder-fired captive bolt. This was undertaken as per the AEC-approved study protocol. This was immediately reported to the AEC who approved continuation of the trial.

for slaughtering livestock for meat production, captive bolts are typically intended to produce immediate insensibility ('stunning') until death occurs from exsanguination (Daly and Whittington 1989). Captive bolts have also been used as single-stage killing methods for livestock (Gilliam *et al.* 2012). Captive bolts have been used most extensively for cattle, and they have become the principal method of pre-slaughter stunning of cattle worldwide (Daly *et al.* 1987).

Captive bolts have also been used for sheep (Daly and Whittington 1989), poultry (Lambooij *et al.* 1999), pigs (Finnie *et al.* 2003), buffalo (Gregory *et al.* 2009), and alpacas (Gibson *et al.* 2015b). Penetrating captive bolts have also been used for killing of over-abundant wildlife, including kangaroos (*Macropus* sp.) in Australia (Sharp *et al.* 2015), white-tailed deer (*Odocoileus virginianus*) in the USA (Schwartz *et al.* 1997), elk (*Cervus elaphus*) in Canada (Shury and Bergeson 2011) and voles (*Myodes* sp.) in the United Kingdom (Frank *et al.* 2009).

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Regardless of the animal species they are applied to, the mechanism of action by which captive bolts render animals immediately insensible remains the same.

3.2.2 Captive bolt mechanism of action

From a mechanistic perspective, there are two types of captive bolts; penetrating and nonpenetrating. Penetrating captive bolts are designed to fire a retractable steel bolt into the head of animals with the bolt penetrating the cranium and entering the brain (Gregory and Shaw 2000). Non-penetrating captive bolts are designed to deliver a concussive force to the cranium sufficient to induce insensibility without penetrating the brain or causing irreversible insensibility (death; Finnie 1995; Gibson et al. 2009).

Under most slaughter conditions, cattle are stunned with penetrating captive bolts, but nonpenetrating units are used under certain cultural conditions (e.g. for halal slaughter; Doyle et al. 2016). An understanding of the mechanics of the insensibility process (known as neurophysiology) is essential to identify the key factors affecting captive bolt performance, and hence for the formulation of desired standards.

3.2.3 Neurophysiology relevant to captive bolts

The specific neurophysiological pathways responsible for insensibility depend on the type of captive bolt used (penetrating vs. non-penetrating). Insensibility is caused by a combination of a bolus of kinetic energy being delivered to the animal's skull, producing insensibility through concussive trauma to the brain (penetrating and non-penetrating; Blackmore 1985), and direct damage to the brain (only penetrating). As penetrating captive bolts are the preferred type for use in cattle and are of most relevance to this project (Patching 2016), non-penetrating models will not be discussed further.

The study of Daly and Whittington (1989) concluded that the impact of the bolt with the cranium is the principal determinant of effective stunning, rather than the penetration of the bolt into the brain tissues. It is now recognised that the kinetic energy (typically measured in joules (J)) imparted to the cranium by the bolt produces insensibility while the actual physical damage by the bolt to specific brain structures is responsible for producing irrecoverable insensibility (death; Gibson *et al.* 2012).

3.2.4 Existing captive bolt propulsion sources

To achieve sufficient kinetic energy delivery to humanely render animals immediately insensible, several power sources are currently used for propulsion of captive bolts. Of these, several modalities are considered appropriate only for small animals (< 5 kg) due to the limited quantity of kinetic energy that they deliver (< 100 J). Modalities used to stun small animals (birds and small mammals) include springs (Sharp et al. 2015) and propane combustion (Sparrey et al. 2014). There are only two propulsion sources commonly used for captive bolts that are applied to cattle: 1) air pressure ('pneumatic') and 2) gunpowder (in the form of cartridges or 'blanks') to propel the bolt (Gibson et al. 2015a).

Pneumatic captive bolt guns are usually limited to use in abattoir environments, while models using gunpowder charges are more often used in farm or field environments (Shearer et al. 2013) or in developing countries (Doyle et al. 2016). Gunpowder units are cheaper and more compact (being hand-held) but legislative restrictions on the use of gunpowder prohibits or complicates their use in some jurisdictions, including Vietnam (M. Patching, pers. comm.). Commercially available pneumatic captive bolts use air compressors and are expensive (~\$20, 000; W. Farr; pers. comm.), heavy (~25 kg (Kentmaster Manufacturing Company 2017), and bulky (usually being bolted to indoor infrastructure and hence not portable; Derscheid et al. 2016).

Field scenarios and abattoirs in developing countries typically require hand-held captive bolts and there are two physical configurations of currently available commercial hand-held penetrating captive bolts (Shearer et al. 2013). These are referred to as "in-line" (cylindrical; e.g. the Matador[®]; Patching 2016), and "pistol grip" (resembling a handgun; e.g. the CASH Special[®]; Gibson et al. 2015a).

3.2.5 Review of devices currently used in Vietnam

Vietnam has recently become an important export market for Australian cattle. For the two most recent financial years, Vietnam has been the second largest cattle export market with 286,811 head sent to Vietnam in 2015/16 (LiveCorp 2016). However, the social licence required to export to this promising emerging market has been threatened by poor publicity in Australia. Negative publicity relating to stunning and killing practices other than use of captive bolts (Keene 2016) have led to increased scrutiny on slaughter of cattle in Vietnam (Patching 2016).

In the thesis of Patching (2016), it was observed that Vietnamese abattoirs routinely used a gunpowder-charged in-line Matador[®] penetrating captive bolt, with red cartridges (imparting an average of 400 J of kinetic energy) for slaughter of exported Australian cattle. However, legislative restrictions on the use of gunpowder cartridges in Vietnam (M. Patching, pers. comm.) have rendered this technology non-viable for the short term. A hand-held captive bolt device that achieves the same performance levels for animals (welfare) and humans (safety, reliability and

affordability) is required. To develop such a device, it is important to have a thorough understanding of factors that determine captive bolt performance.

3.2.6 Factors affecting performance

Gibson *et al.* (2015a) observed that the performance of captive bolt stunning in rendering animals insensible can be affected by the following factors: (a) selection of the appropriate captive bolt/cartridge combination for the species and/or animal class; (b) accurate placement of the shot; (c) experience of the stunner operator; (d) storage of the stunner and cartridges in dry conditions; and (e) regular maintenance of the stunner. These factors, other than selection of appropriate equipment, can be managed through staff training. However, it is likely that without access to equipment that reliably delivers the appropriate kinetic energy, humane stunning outcomes will be difficult to achieve under expected operating conditions.

3.2.7 The central role of kinetic energy

Of all factors assessed that may influence captive bolt performance, kinetic energy has consistently been found to be the most important determinant of animal welfare outcomes (Blackmore 1985; Daly *et al.* 1987; Gibson *et al.* 2015a). Similar conclusions have been reached for humane shooting of animals (using free bullets rather than captive projectiles; Hampton *et al.* 2016). Bolt velocity and bolt weight are the two variables that determine kinetic energy delivery, with bolt velocity being the most important determinant of energy levels achieved (Daly *et al.* 1987) according to the equation E_k = $\frac{1}{2}mv^2$. For animal welfare outcomes, other variables such as bolt diameter or depth of penetration are likely to be less important. Accordingly, we designated minimum kinetic energy levels as the central performance standard to be achieved by any newly developed captive bolt modality during this project.

3.2.8 Minimum performance standards required

Based on the above review of factors affecting captive bolt performance broadly, and conditions encountered in Vietnamese abattoirs specifically, the following standards were elucidated. It is important to note that the thesis of Patching (2016) observed that the gunpowder captive bolts currently used in Vietnam deliver 400 J of kinetic energy per shot. However, the review of Gibson et al. (2015a) found that multiple cattle captive bolt models were considered humane when they delivered \geq 300 J of kinetic energy. Accordingly, we designated 300 J as our minimum limit for kinetic energy delivery.

The unit needs to:

- 1. deliver \ge 300 joules (J) of kinetic energy (Gibson *et al.* 2015a).
- 2. contain a bolt \ge 210 grams (g) in weight (Gibson *et al.* 2015a).
- 3. have a bolt head width \geq 11 mm (Gibson *et al.* 2015a).
- 4. deliver the bolt at a peak velocity \geq 50 metres per second; (Gibson *et al.* 2015a).
- 5. penetrate \geq 70 mm into the head of a live cow (Gibson *et al.* 2015a).

This unit also needs to be safe to use, relatively cheap to purchase (\$US2,000), be compact (< 50 cm), light (< 5 kg), durable and use cheap, freely-available consumables in a device that does not resemble a firearm.

3.3 Choosing an alternative power source

Literature indicated that development of an independent, hand-held pneumatic captive bolt was feasible. Such a system requires the unit to carry a cylinder for compressed air that can be charged at sufficient pressure and volume to deliver the required power to the bolt on release of the trigger. The existence of 'big-bore air guns' that are capable of delivering more than 600 J of energy was evidence that a pneumatic captive bolt performing to desired specifications was feasible.

Importantly, cheap systems for re-pressurising spent gas canisters were identified. This potentially allows for operation of a pneumatic captive bolt in sites without electrical power (to operate a compressor) and (more importantly) removing risk of electrocution from operation of electrically-powered equipment on or around the (wet) kill floor in abattoirs. Ability to recharge spent canisters will also reduce the cost of operation and this will aid compliance. We identified industry standard quick connect adaptors, that will enable direct swapping of gas canisters in the field in the event that ability to recharge is not available and gas supplier networks in target countries that can supply works with master commercial supply cylinders each containing well over 1,000 discharges.

Swapping the gunpowder firing chamber with a compressed-air-based power unit is insufficient on its own to convert a gunpowder-based captive bolts to compressed air. The power release profiles from gunpowder and compressed air differ in important aspects. The rate of gas expansion and the force delivered to the projectile (bolt) is more rapid following gunpowder ignition than from the release of compressed air. Practically, this means that a pneumatic captive bolt requires longer travel distances until it reaches a velocity that provides the required stunning power. This was the main reason the Tomahawk DT did not provide sufficient power for the bolt to penetrate the skull of large cow cadavers. Modifications to the bolt, chamber and/or barrel are necessary to ensure that a pneumatic captive bolt will deliver this required force at the point of impact. The length of the captive bolt barrel will likely be longer on a hand-held pneumatic captive bolt than for a gunpowder-powered equivalent. Unfortunately, this is a necessary requirement for any pneumatic device.

There are many commercial companies developing and supplying pneumatically powered pistons and other equipment to industry and many of these are adaptable for use in a pneumatic captive bolt whilst maintaining device compatibility to existing standards while still meeting the physical performance specifications of gunpowder-powered captive bolts. Paintball gun technology is applicable. A paintball gun is a hand-held and portable pneumatically-powered gun. However, these are legally restrained to deliver an exit speed of 90 m/s – but the pneumatics are capable of much higher speeds and more power. Modern paintball guns use compressed air (often called 'nitrogen' as air is 78% nitrogen) contained within a High Pressure Air system that can be compressed to 860 psi (~60 bar). Compressed air provides advantages in easier regulation of pressure and gases are safer and more stable (in correlation with temperature variations) than CO₂. The availability of commercial pneumatic piston systems is expected to assist the development of prototype hand-held pneumatic captive bolts and (should testing prove successful) to enable cost-effective production of commercial units. These findings combined with the innate features of pneumatic power are the basis of our focus on the development and testing of only pneumatic-powered prototype captive bolts.

3.4 Prototype design

Compressed air captive bolt prototypes were developed and designs capable of achieving bolt exit velocities similar to gunpowder-powered devices were identified. The main features are the unit: can be operated using compressed air or compressed CO_2 (both readily available in market as portable cylinder supply); operates at moderate pressure levels (10-20 bar); pressure levels can be varied according to animal size and requirements (by adjusting internal pressure); is portable and able to be operated by a single user; is easy to maintain and where possible uses off-the-shelf parts (accessible from non-specialised suppliers).

The device has a modular construction; separated primarily into a front-end (bolt mechanism and housing) and a back-end (compression chamber, charging mechanism and trigger). Materials include aluminium 6000 series, stainless steel (SS304) and brass (PB1). There are some bespoke items that are manufactured using specialised equipment and dyes; necessary to ensure safety and functionality.

3.4.1 Key features

Key features include:

- 1 A manual priming system that requires moderate force to prime. The device cannot be charged with compressed gas or fired without priming. This provides extra safety
- 2 An in-lane system lacking a pistol grip with a trigger on the compression unit operated by the back hand.
- 3 A pressure gauge mounted onto the compression unit. This supports infinitely variable pressure charging and delivery (to suit the animal), and to provide a means of checking there is adequate pressure in the unit before discharging the device.
- 4 A pressure safety release for accidental pressure overload (> 20 bar).
- 5 A quick-connect air socket (industry standard) is used to deliver compressed air from the cylinder reservoir to the compression unit. The gas flow is managed by a one-way valve that is built into the connector tubes. This makes the product compatible with most compressed air systems in the market.
- 6 A bolt retention system that prevents the bolt from ever leaving the bolt housing (i.e. from becoming a projectile). Built-in spring and rubber dampening mechanisms assist reduced jarring should the device be 'dry fired' (not recommended).
- 7 A simple maintenance regime that revolves around cleaning and lubrication of the (separate) bolt housing and o-ring maintenance and lubrication for the compression chamber.
- 8 An internal magnet system (within the compression chamber assembly) that holds the bolt inside the bolt assembly opposed to the compression chamber release valve. This ensures maximal force is applied to the bolt upon discharge and allows the device to be effectively operated pointing downwards.

3.4.2 Captive bolt assembly (front-end)

The front-end module is a 40 cm barrel containing an innovative sub-assembly; a "traveller" captive bolt (see Figure 1). The traveller captive bolt is designed specifically for this product. It supports the use of lower pressure whilst maintaining high terminal bolt velocity and energy. The traveller bolt uses the bolt's initial inertia combined with pressure multipliers along the travel route to maximise bolt velocity at the housing exit point.



Figure 1. Transparent 3D view of the front-end

The traveller captive bolt is retained in place by neodymium magnets and has in-built redundancy for shock amelioration (rubber tube and strong stainless steel spring). Bolt length is 250 mm. The maximum bolt exit length (penetration) is 100 mm (as per requirements for cattle captive bolts). The weight of the front-end module is less than 1.5 Kg. The compression chamber is heavier, and this ensures device weight is distributed towards the back and this provides better operator ergonomics and safety.

3.4.3 Pneumatic power unit assembly (compression chamber; back-end)

The back-end compression chamber is the main unit (see Figure 2). This is where gas pressure is stored. This incorporates an innovative valve system developed for this product. This valve seals using surface contact. The back-end has three main components: a compression chamber, a valve and a trigger mechanism. The back-end has been designed for field use; it can be easily serviced in the field by relatively unskilled operators.



Figure 2. 3D representation of the back-end

The operator can connect the air supply (easy-connect fittings), read pressure inside the chamber from the gauge, and observe the safety release valve (operates in the event the device be overfilled). This is presented in Figure 3.



Figure 3. Compression chamber fill valve, safety valve and pressure gauge

3.4.4 Computer Aided Design (CAD) plans

The product CAD designs are produced according to best practice for design in engineering and manufacturing (see Figure 4 for an example)². Special attention was dedicated to design to aid toll manufacturing. As an example, the seal of the compression chamber relies upon apposition of perfectly matching surfaces. This is supported with o-ring gasket seals and redundant external transversal securing rods. All contribute to ensuring the compression chamber can hold pressure during field use and this brings additional safety and functionality performance and assists (especially) in the assembly process by allowing larger component tolerances. Similarly, the trigger has a basic latch system. The trigger spring can be adjusted or changed to match individual operators. This flexibility comes without need for major design change required; the CAD offers extra flexibility in specifications to allow adaptation for operation and/or for manufacturing. The valve sub-assembly design provides: trigger-initiated rapid pressure release, shock absorption from recoil and valve arming features.

² Note that the complete set of CAD drawings are not included in this report in order to protect project IP



Figure 4. CAD drawing of component.

3.4.5 Device operation - basic summary of procedures

It is important that basic procedures are followed to ensure the device operates in the desired manner. These are summarised below:

1. The T-Bolt20 pneumatic captive bolt is stored and transported in a disassembled state with components packaged into a bespoke aluminium carry case with foam padding (Figure 5).



Figure 5. T-Bolt20 carry case.

2. The unit is to be visually inspected to ensure all components are present and undamaged. The device should be lubricated using recommended lubricant (gun oil) before using the unit for the first time and the start of each day of operation (Figure 6). A low-pressure charge of the compression unit with dry firing (without the bolt assembly attached) is recommended to distribute the lube and to seat the o-rings into their housing.



Figure 6. Lubrication maintenance of compression chamber valve.



3. The bolt assembly can then be screwed into the compression chamber (Figure 7).

Figure 7. Attaching the bolt assembly to the compression chamber.

4. The compressed gas cylinder can be connected to the compression chamber and the required pressure of compressed gas delivered into the unit (Figure 8).



Figure 8. Filling the compression chamber with gas.

5. The device has two states: armed and ready; disarmed. The device default is to be in the disarmed state (Figure 9). This prevents retention of gas in the compression chamber and prevents the device from being stored in an active state. Arming requires the arming button to be pressed (Figure 10). This requires reasonable (one-handed) force and serves as a safety feature. An extra safety feature is included (in case the operator forgets and stores the device charged with compressed air). The device allows compressed gas to slowly leak away over a few hours; thereby reducing danger of accidents in case a charged device is left unsecured.



Figure 9. Arming button in disarmed state



Figure 10. Arming button in armed state

3.5 Benchtop performance testing

Benchtop studies identified the following:

- Maximum velocity occurs later in travel and at a longer distance from the origin under pneumatic power compared to a gunpowder-fired device as the rate of acceleration is less. This has implications for the length of the bolt assembly; pneumatic devices will always need to be longer than gunpowder-fired devices.
- Force delivered to the bolt is a complex function of bolt weight, bolt diameter, chamber volume, air pressure and distance travelled. Longer chambers than for gunpowder-fired devices are required. The prototype device is 45 cm and weight < 5kg and this has good ergonomic characteristics under two-handed operation.
- Air pressure above 10-12 Bar (145-175 psi) is likely required to provide sufficient power to the bolt. Air pressures below 20 bar ensure the device remains portable. There are commercially available portable high-pressure air cylinders capable of pressures in excess of 3000 psi (~240 Bar) but these are fixed-in-place (heavy) systems.
- 4. Force dampening systems included in gunpowder-based bolts require modification to ensure minimal loss of pneumatic pressure before the stunning point is reached by the pneumatic bolt. A dampening system beyond the maximum stunning point range remains necessary to prevent the full force of an unhindered travelling bolt (e.g. air shot) from damaging the unit or from injuring the operator. Elastomer bumpers, polyurethane rubber and springs have been used to provide this feature.

The prototype device built under these limitations and to meet desired specifications was tested to determine both the power distribution and amount (weight) of compressed gas used per discharge distributions. A series of tests were conducted. A laser meter (Super Securitest 3000 by Termet) measured bolt exit velocity and bolt kinetic energy was estimated using standard equations. However, laser meters used were unable to estimate accurate exit velocities at these very high velocities, therefore a substrate penetration test was used to compare bolt power to gunpowder-

fired captive bolt. The depth of bolt penetration into a dense substrate (e.g. wood) was compared between modalities to ensure that the pneumatic bolt at least provided an equivalent power of penetration to gunpowder-fired devices. The substrate penetration tests on master samples (e.g. rectangular wooden beams) show consistent imprint, in fact we established that a certain depth (around 11-12 mm) of the imprint left by the bolt on the wooden sample is able to deliver a penetrating blow on a test cadaver.

The device was found to consistently use an average of 14 grams of CO₂ per discharge (14–20 grams range) and the 1.4 Kg small storage cylinder safely held over 30 discharges from a 0.8 L compressed air tank. This effectively ensures the cost per use will be low and that a single cylinder will provide multiple discharges. Effectively this means an abattoir main gas cylinder will store potentially many thousands of discharges and this provides an important buffer against bottled gas supply chain problems in market. Mature bottled gas supply chains exist in countries such as Vietnam and this ensures that an effective, reliable and competitive supply contract can be negotiated by individual abattoirs.

The final prototype design was found to consistently use an average of 14 grams of CO₂ per discharge and the 1.4 Kg small storage cylinder safely held around 30 (equal) discharges (Figure 11).



Figure 11. Gas weight used per discharge by number of discharges

3.6 Cadaver testing

The final design was assembled. This prototype device, suitable for toll manufacturing and supported by a complete set of CAD design plans was named the T-Bolt20. The T-Bolt20 was tested on a set of complete cow heads obtained from recently-processed cows from a local knackery. Heads ranged in size and breed (most were large Friesians), were fresh and retained skin covering. The heads were individually propped against a wooden brace on the ground, the captive bolt was positioned and fired into the head as per normal use. The length of bolt penetration was measured. The bolt provided complete penetration to the brain stem in all subjects (including the largest of cows), across all operators and at all pressures above 15 bar. The T-Bolt20 was approved for live animal testing based on the results of cadaver testing

3.7 Field trial (live cattle) testing

3.7.1 Study design and Animal Ethics Committee approval

The Wildlife and Small Institutions Animal Ethics Committee (WSAIEC approval 15.18) approved conduct of a stunning field trial with 10 cattle sourced from a commercial farm. The protocol required access to approved back-up euthanasia devices, recording of recognised measures of animal insensibility, pithing euthanasia (back-up) for all animals and single-animal processing.

Insensibility was assessed using combined information from corneal and palpebral reflexes, muscle tone, pupillary light reflex, breathing and heart rate. Penetrative stunning effectiveness was assessed by measuring skull penetration depth and position. The data recording sheet is presented in Figure 12.

W.LIV.30145		Captive	Bolt Field Trial		WSAIEC Application 15.18			
EUTHANASIA RECORD FORM								
LOGISTICS	Date	Time	Location]				
ANIMAL	Breed	Sex	Estimated weight	(Kg)				
EQUIPMENT	Model #	Pressure (KPs)]					
OPERATOR	Name							
SKULL PENETRATION	Yes	No]					
LOSS OF CONSCIOUSNESS	Absent	Reduced	Normal]				
TIME TO LOSS OF CONSCIOU	SNESS	Seconds]					
CORNEAL REFLEX AFTER STU	INNING	Absent	Reduced	Normal				
MUSCLE TONE AFTER STUNN	IING	Absent	Reduced	Normal				
REGAINED CONSCIOUSNESS	Yes	No]					
PITHING REQUIRED	Yes	No]					
ABSENCE OF HEART BEAT	Yes	No]					
ABSENCE OF BREATHING	Yes	No]					
TIME TO DEATH	Seconds							
POST-MORTEM FULL SKULL PENETRATION	Yes	No]					
OVERALL EFFECTIVENESS	Effective	Partly effective	Ineffective]				
COMMENTS								
RECORDER	Name							
Herd Health Pty Ltd					Page 1/1			

Figure 12: Data recording sheet for field euthanasia trial

3.7.2 Study conduct

The live-animal study was conducted on a commercial cattle farm in Glen Alvie, South Gippsland, Victoria on 20th and 21st March 2019. Seven animals were processed on the 20th March and three animals on the 21st March.

Nine of the ten animals were effectively stunned using the T-Bolt20 pneumatic stunner. One animal was ineffectively stunned. This was subsequently found on post mortem due to incorrect positioning of the bolt against the head, resulting in the bolt failing to enter the brain. This animal was immediately euthanised using a back-up (gunpowder-fired) captive bolt within 20 seconds of the failed first stun. The animal moved its head slightly before firing and this resulted in misplacement of the bolt into the head. The failure was assessed as due to late animal movement and not due to any deficiency of the pneumatic captive bolt. Animal movement resulting in mispositioning or

misplacement of the captive bolt are occasional problems that can occur when using any form of captive bolts.

The other nine animals experienced instantaneous loss of consciousness (as measured by changes to reflexes, responses and key physiological functions such as breathing) following application of the pneumatic stunner. Animals were immediately pithed after unconsciousness was confirmed and death (cessation of heart beat) proceeded X-Y minutes after stunning. Post-mortem examination indicated complete skull penetration with alignment of bolt penetration with the brainstem in each of the nine successfully euthanised animals.

The pneumatic stunner was assessed to have performed reliably across all cadaver and live animal applications. Adequate force was delivered on all occasions. The safety features of the device - primarily the priming button and pressure gauge - ensured the device was only used when capable of inducing immediate insensibility each subject animal. The device was able to be effectively manipulated by the operator and each animal was able to be suitably restrained in a head bale supported by halters to ensure safe and effective use.

The animal trial component confirmed that the pneumatic device met the required performance standards for a captive bolt. The T-Bolt20 device was assessed as being ready for market as a result of this series of studies.

3.8 In-market (Vietnam) abattoir demonstration

An in-market demonstration was undertaken in Vietnam (Ho Chi Minh City) between 12-18 July 2019. This demonstration focused on three objectives: determine the most suitable gas supply system for Vietnam; demonstrate the device in an approved abattoir and collect information from end users on the most suitable way for the system to be used, device modifications; and identify local agents to assist service the market. All objectives were achieved.

The T-Bolt 20 used for the Vietnamese demonstration is presented in Figure 13.



Figure 13: T-Bolt20 used for demonstration in Vietnam. Note this includes an adapted paintball gas bottle. This will not be provided or used in the commercial product in Vietnam.

Gas supply problems were identified. Only one paintball company remains active in Vietnam and the supply of paintball gas bottles is both heavily regulated and the bottles found to be unsuitable (unsafe) for use with the T-Bolt20. An alternative was identified in bottled CO₂ for welding (see Figure 14 and 15). A bespoke adapter was commissioned from a precision engineering shop to allow connection between the (standard) CO₂ cylinder and the supply line for the T-Bolt20. This device was successful and allows use of varying sized bottles as abattoir supply (see Figure 16). The final configuration used for the abattoir demonstration is presented in Figure 17.



Figure 14: Examples of welding CO₂ bottled gas supplies in Vietnam. Note the variable bottle sizes



Figure 15: CO₂ welding supply bottle regulator used in Vietnam



Figure 16: Bespoke precision-made adaptor for connecting CO_2 welding supply bottled gas to T-Bolt20 supply line



Figure 17: Use of bespoke precision-made adaptor, bottled CO₂ (welding supply) and T-Bolt20 supply line connected to the T-Bolt20 in a Vietnamese abattoir

A modified value is recommended for the bottled CO_2 connector. This will be a slow-release value (as only 10-15 grams of gas are required to fill the T-Bolt20). Slow release provides for added operator safety and will reduce risk of freezing of the T-Bolt20 supply value (liquid CO_2 is <-55°C). This will be incorporated into the bespoke adaptor.

A total of ten animals were stunned in Vietnam. The device performed according to specifications on every use. The local slaughterman was trained in use of the device (2 minutes) and he used the device on three of the ten animals.

Observers and end users provided the following recommendations for use:

 The device would ideally be shorter. One suggestions was for the compression chamber and barrel assembly to be in parallel and not in series. This will require a modification to the valve and an adaption to the casing. It will also allow a smaller (10-50 Kg) gas supply cylinder to also be stored in a cage suspended under the ceiling near the suspension apparatus attachment. This supports easy re-charging of the device whilst still allowing some portability in the device (i.e. the device can be disconnected from the suspension and used freely should need arise).

- 2. The device should be suspended from the ceiling to allow ergonomic use. This would allow the device to be heavier than the current 4 Kg weight. The barrel (at least) can now be constructed from stainless steel. This will both improve device robustness and be more suitable for food production.
- 3. An enclosed finger-operated trigger (currently there is a thumb trigger) was desired.

All suggestions have been well received and designs for modifications are in progress. We envisage another demonstration of the modified device before releasing to the market. The demonstration was a success and all objectives were achieved. The market was receptive to the device and enthusiastic to see the final market-release device.

3.9 Supply chain analysis

3.9.1 Abattoir logistics

An abattoir needs a supply of compressed gas at sufficient pressure to operate the device. One option may be to install air compressors at abattoirs using the pneumatic bolt. We do not recommend this option for two main reasons:

- Most basic air compressors deliver 10 bar or less (sufficient to operate most pneumatic tools); which is insufficient for requirements for the captive bolt. Specialised (SCUBA) compressors are required to provide pressure in the range required. Such compressors are expensive (around \$AUD15,000) and this is likely beyond the capacity of small abattoirs.
- 2. Humidity affects performance of the device. Water inside the compression chamber will affect the operation of the valve system, promote corrosion and reduce the pressure release profile of a discharge in poorly maintained devices over time. Any compressor located at an abattoir will most likely be compressing (non-filtered) humid air especially in the tropics.

3.9.2 Gas supply chain

Bottled gas supply chains are mature in most markets. The device can operate using any compressed gas. The non-flammable options are compressed CO_2 and compressed air. There are various advantages and disadvantages to each gas that are summarised below:

- 1. Compressed CO₂ is liquid under pressure whereas compressed air is a gas under pressure.
- 2. Using compressed CO₂ results in greater heat exchange between the device and the source. This can result in freezing of the fill valve mechanism (preventing closure - requiring the source cylinder to be turned off), and condensation of water within and around the device on filling. Compressed air does not bring as much heat exchange issues to filling of the compression chamber; making compressed air easier to use.
- 3. Bottled compressed CO₂ supply chains are well developed and larger than for compressed air. Compressed CO₂ is used in welding and the market and supply chain tends to be larger, more widely dispersed and mature. Compressed air is used mostly for respiratory applications. This includes hospitals, home nursing and SCUBA uses. The market is smaller than for bottled CO₂ and likely to be less extensive (less likely to be present in rural settings) and gas per unit weight more expensive than for bottled CO₂.

- 4. More gas is present in a cylinder of compressed CO₂ than in a cylinder of compressed air (one being liquid and one being gaseous). This would require more cylinders of compressed air to be carried by an abattoir than required for compressed CO₂. This may have logistics and supply implications.
- 5. Supply contracts may differ for compressed CO₂ than for compressed air. Cylinder purchase may be required, and this will likely be more expensive for compressed air (more cylinders are needed). The cost of gas on a weight volume will vary with compressed air typically cheaper than compressed CO₂, but this may be market-specific.

4 Discussion

4.1 General findings

The following comments are made:

- 1. Non-gunpowder power technology exists in a form that is suitable for use as the power source for a captive bolt euthanasia device for large animals.
- 2. Pneumatic power systems offer the most reliable combination of power, reliability, low-cost equipment, manageable and efficient supply chains, ease of maintenance and acceptability for registration as a lethal device for relevant authorities and government.
- 3. Pneumatically powered systems have different energy release profiles to gunpowder powered systems that necessitate different architecture. The most obvious difference is that pneumatic systems require longer bolt chambers to allow for slower. acceleration, and to ensure bolt velocity reaches required levels at impact. This is because bolt acceleration from pneumatically powered sources is slower than for gunpowder powered sources. The extra length of pneumatic captive bolt devices are accompanied by an increase in weight of the device. However, single-person, mobile operation is not compromised through the choice of pneumatics.
- 4. Pneumatic systems require a compression chamber that is manufactured to high standard (small tolerance for parts out of specification) to ensure that effective seals form and that pressure can be retained and delivered effectively.
- 5. Pneumatic captive bolt systems must operate at pressures between 15-25 bar in order to deliver sufficient energy to the bolt to meet requirements for effective stunning of large animals. This is more than the maximum pressure generated using a basic compressors (e.g. as used to fill tyres or operate pneumatic hand tools).
- 6. Well-designed pneumatic systems support variable power delivery. The power delivered is a function of the volume and pressure of gas delivered by the system and the weight of the bolt. The diameter of the bolt and the free travel length of the chamber also determine the energy on impact. By adjusting the pressure of gas delivered to the bolt infinitely variable energy can be delivered to the bolt and therefore to the animal. This allows the power to be adjusted according to the animal and requirements for the stun. This offers potential for percussive stunning in markets that require Halal slaughter whereby the power can be managed to minimise risk of skull fractures (which renders the carcase non-Halal).

- 7. Pneumatic systems can operate of many gases. The most suitable non-flammable options are compressed CO₂ and compressed air. Compressed CO₂ is efficiently stored (being liquid at room temperature), cheap and has mature cylinder supply markets in most countries. It is, however, more difficult to use as it is prone to freezing on filling child cylinders. This can result in valve freezing and resultant difficulties in closing. Compressed air remains in the gaseous phase under pressure. As such, it is easier to transfer to child cylinders, associated with less freezing of equipment in contact and more reliable delivery can ensue. A lower weight of compressed air is present in a cylinder than for compressed CO₂. Systems that use compressed air may require more storage cylinders than systems built around compressed CO₂.
- 8. A captive bolt has high-speed componentry. As such, regular maintenance is essential to ensure reliable operation. Dirt and lack of lubrication can result in incomplete transfer of energy to the bolt with ineffective stunning a risk. Regular maintenance is essential for any captive bolt device. Pneumatic systems have the added requirement of maintenance and storage to ensure the compression chamber maintain effective seals. The inclusion of maintenance for o-rings and cylinder components is essential but not onerous to maintain a working system.
- Custom valves and bolts were required for the development of a portable, single-operator, hand-held, pneumatically-powered captive bolt suitable for use on large animals such as cattle. These have been developed, extensively tested, custom manufactured and incorporated into the T-Bolt20.
- 10. The T-Bolt20 was proven to be highly effective across a wide range of cattle of varying sizes in a controlled field study.
- 11. The Computer Aided Design (CAD) plans for construction and assembly of the T-Bolt20 have been developed and are provided with three fully constructed and operational devices (with self-contained storage cases). This is supported by an extensive training manual and training videos.

4.2 Pneumatic captive bolt project summary

The project has met all required objectives as follows:

RequirementStatusA report summarising the current animal welfare
standards required for humane cattle stunning
devices.Completed in fullA report summarising the alternative (non-
gunpowder) power sources currently used for
captive bolts and a review of alternative power
technologies that may be used as replacement for
gunpowder.Completed in full

Requirement	Status
A report outlining the design, construction, and bench-top testing results of prototype captive bolts and an assessment of suitability for commercial manufacture and use. The objective of the report will be to inform the selection of the design or designs for commercial manufacture and identify manufacturing processes required (Go-No Go point).	Completed in full. This was extended to include the assessment of an existing product which re-entered the market in late 2016
A report of the field trials evaluating the selected prototype(s) performance as a captive bolt using:	Completed in full
post-mortem evidence using cattle cadavers, and	Completed in full
ante-mortem evidence using live cattle, in a controlled Australian abattoir field trial. Field-test results would be compared to required animal welfare standards and desired technical specifications. The report will document the assessment of device performance against: animal welfare requirements, practical use specifications, safety (human and animal) and suitability for commercial manufacture (Go-No Go point).	Completed in full
A design and manufacturing plan for the commercial production of captive bolts. This will include a description of the necessary registration and accreditation certification, packaging requirements and documentation.	Completed in full. CAD designs and a manufacturing plan presented. Device accreditation and registration requirements presented with CAD. Three working devices, consumables and manuals are also provided
An optional demonstration of the technologies to authorities in Vietnam	Completed in full.

5 Conclusions and recommendations

This project has delivered a field-tested, compliant, reliable, effective, easily-modified and low-cost, pneumatically-powered captive bolt device along with associated manufacturing and assembly plans as per the terms of reference.

This device will likely be acceptable to regulatory authorities in all countries.

The device is suitable for adaptation to a percussive stunning device for Halal slaughter of large animals. We recommend that this adaptation be developed as a next step.

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