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History and best practices of captive bolt euthanasia for swine

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ABSTRACT

The definition of animal welfare includes how an animal dies. As such, euthanasia is intrinsically linked to animal welfare, and ensuring a good death through effective, safe, and validated practices is a critical piece of promoting positive animal welfare. The objective of this review is to provide a better understanding of the literature on the euthanasia of swine via penetrating captive bolt (**PCB**) and nonpenetrating captive bolt (**NPCB**), as well as a history of captive bolt use, and indicators of sensibility and insensibility. To do this, we performed a systematic review that included 30 peer-reviewed articles and 17 other publications. NPCB devices have been validated as an effective single-step euthanasia method for neonatal and preweaning swine, as well as a two-step euthanasia method for nursery swine. PCB devices have been validated as an effective euthanasia method for nursery and market swine up to 120 kg, but further investigation is required for the use of captive bolt devices on mature breeding sows and boars.

Key words: captive bolt, euthanasia, swine, welfare

INTRODUCTION

The word euthanasia comes from the Greek term *euthanatos*, which translates to an easy death (Merriam-Webster, 2021). The American Veterinary Medical Association (AVMA, 2020) describes euthanasia as "a good death" and it has also been described as "the humane process whereby the [animal] is rendered insensible, with minimal pain and distress, until death" (NPB and AASV, 2016). Euthanasia is also linked very closely with animal welfare, which is defined by the World Organization for Animal Health (OIE) as "the physical and mental state of an animal in relation to the conditions in which it lives and dies" (OIE, 2021). To further connect euthanasia to animal welfare, Yeates (2010) describes euthanasia as "killing an animal in its own (welfare) interests." Ultimately, a humane death is part of a good life (AVMA, 2020).

The description of euthanasia from the National Pork Board and American Association of Swine Veterinarians (NPB and AASV, 2016) highlights that euthanasia has two main goals: first, the animal must be rendered immediately insensible, and second, death must be achieved. The terms insensibility and unconsciousness are often used interchangeably (Grandin, 2020; Terlouw, 2020). In this review, the term insensibility is used. There is an important distinction that must be drawn between stunning and euthanasia. A method—such as penetrating captive bolt (**PCB**)—may be acceptable and approved for stunning a specific type of animal when insensibility reliably lasts until the animal is exsanguinated as part of the slaughter process. However, for a method to also be acceptable and approved as a single-step euthanasia method, insensibility must be achieved as well as death without any additional action. Methods that do not achieve death following insensibility on their own may be used in a two-step method (AVMA, 2020). For example, a PCB may be used to render an animal insensible, but a second PCB application, pithing, or exsanguination may need to occur subsequently to ensure the animal dies and does not regain sensibility in the process of dying.

The AVMA classifies methods of euthanasia as acceptable, acceptable with conditions, and unacceptable based upon 14 criteria, some of which are relevant to animal welfare—for example, a loss of sensibility with minimal pain and distress, time to insensibility, compatibility to species, age, health of the animal, and reliability (AVMA, 2020). When a method is classified as "acceptable," it is a method that consistently produces a humane death as a sole means of euthanasia (AVMA, 2020). A method that is "acceptable with conditions" can indicate that a method 1) may have additional requirements (such as a second step or an adjunctive method) to consistently achieve a humane death, 2) may present an increased risk to the person administering the euthanasia method, or 3) present a greater risk for operator error (AVMA, 2020). In addition, methods that have not been well documented in the scientific literature, in a general sense or for a specific type of animal, may also be "acceptable with conditions" pending validation (AVMA, 2020). When all criteria for a method of euthanasia have been met, an "acceptable with conditions" method is

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considered equivalent to an "acceptable" method. An "unacceptable" method of euthanasia is inhumane in a circumstance or one that presents a substantial risk to the operator (AVMA, 2020). Beyond these three classifications, "adjunctive methods" are defined as techniques that may not be used as a method of euthanasia alone but can be used alongside other methods (AVMA, 2020).

Using validated euthanasia methods is important to minimize the risk of failure—promoting positive animal welfare and protecting worker mental health as much as possible. However, it can be unclear how much of current practice is based upon peer-reviewed publications and how much comes from generally accepted practices. The objective of this review is to provide 1) a brief history of captive bolt use, 2) a current understanding of the indicators of sensibility, and 3) a better understanding of the literature on the euthanasia of swine via PCB and nonpenetrating captive bolt (**NPCB**).

MATERIALS AND METHODS

A search of peer-reviewed literature was conducted using Web of Science via the University of Wisconsin—River Falls and University of Minnesota library systems between January 2020 and January 2022. Keywords searched included: "captive bolt," "stunning," "euthanasia," "swine," "cattle," "porcine," "bovine," "sheep," "goat," "ovine," and "caprine." No limits regarding the year of publication were set. The search was then refined by combining these keywords. The number of articles returned from each search on Web of Science is outlined in Table 1. Articles focusing on methods of stunning and euthanasia other than the captive bolt (e.g., electrical stunning, CO_2 stunning, barbiturate overdose, blunt force trauma, etc.) were excluded. Articles related to the captive bolt stunning and euthanasia of species other than swine were assessed for relevance. In addition, references known to the authors relating to the captive bolt stunning and euthanasia were included. Due to the limited peer-reviewed literature regarding the captive bolt euthanasia of swine, other relevant literature, such as industry guidelines and conference abstracts, was also evaluated and included in the review, as appropriate. The criteria for selecting articles for inclusion were a combination of overall relevance to captive bolt stunning and euthanasia, as well as more specific relevance to indicators of insensibility, history of captive bolt use, differences in placement, and literature focused on swine. A total of 47 pieces of literature are included in this review.

Table 1. Keywords searched in Web of Science and corresponding number of results

Keywords searched	Results
Captive bolt	319
Captive bolt AND stunning	182
Captive bolt AND euthanasia	78
Captive bolt AND swine	22
Captive bolt AND cattle	134
Captive bolt AND porcine	8
Captive bolt AND bovine	23
Captive bolt AND sheep	50
Captive bolt AND goat	9
Captive bolt AND ovine	0
Captive bolt AND caprine	1
Stunning AND swine	167
Stunning AND cattle	301
Stunning AND porcine	181
Stunning AND bovine	63
Stunning AND sheep	189
Stunning AND goat	27
Stunning AND ovine	7
Stunning AND caprine	2
Euthanasia AND swine	209
Euthanasia AND cattle	267
Euthanasia AND porcine	202
Euthanasia AND bovine	183
Euthanasia AND sheep	255
Euthanasia AND goat	74
Euthanasia AND ovine	57
Euthanasia AND caprine	14

HISTORY OF THE DEVELOPMENT AND USE OF CAPTIVE BOLT DEVICES

History

The practice of stunning animals, in some form or fashion, has existed for a long time, although the specific start date of such activities is unknown. Some estimate it began as early as the 11th century (Woods, 2012) and others have described the first mandate of the practice in the 14th century (Lambooy and Spanjaard, 1981). Despite uncertainty regarding the exact start date of preslaughter stunning, the practice is well documented in Great Britain beginning in the 1800s when an increased societal concern for animal suffering during the slaughter process developed. It was part of a broader animal welfare movement that occurred congruently with the industrial revolution, urbanization, and growing demands for meat, in part because individual members of society had more resources than before (MacLachlan, 2005). At that point in time, there were three common methods of physical stunning: sledgehammer, puntilla, and poleaxe (MacLachlan, 2005; Karczewski, 2011). In addition, exsanguination without stunning was common (MacLachlan, 2005). The sledgehammer method was a form of concussive stunning, which is thought to be the oldest method of stunning (Lambooy and Eikelenboom, 1983). The sledgehammer method was, to some extent, similar to the NPCB methods employed today. However, issues with inconsistent induction of insensibility were prevalent due to the nature of the method requiring sufficient human accuracy for placement on animals that were often moving or poorly restrained, as well as adequate to deliver a blow that was powerful enough to result in insensibility (MacLachlan, 2005). The puntilla method, also called pithing or nape-stab, involved the severing of the spinal cord in the neck region with a short, dagger-like knife, often in a placement behind the poll of the animal's head or in the nape of the animal's neck (MacLachlan, 2005). It is important to note that this method of stunning did not actually provide a stun to the animal, but rather caused paralysis, something that was unknown at the time. Stunning with the poleaxe, a tool with a long handle, and two-sided head with one sharp, pointed end opposing with a blade, rounded, or square end, involved the utilization of the pointed (non-blade) side of the tool to deliver a blow to the head of an animal. This pointed tool ultimately penetrated the animal's skull. The poleaxe stunning method served as the foundation for the series of developments that lead to the PCB devices used for stunning and euthanasia today (MacLachlan, 2005). While the poleaxe offered many advantages over the sledgehammer and puntilla, it was not without faults. The poleaxe had the benefit of providing both a concussive blow and penetration of the skull into the brain, but—like the sledgehammer—insensibility was dependent on operator strength and precision of where the tool struck the animals' head. As a result, multiple attempts were often required to achieve insensibility (Karczewski, 2011; Houses of the Oireachtas, 2021). In an attempt to rectify these issues with the poleaxe technique, a slaughter mask (Bruneau) was first developed in 1872. Fitting the mask to each animal was required, which was believed to be distracting and stressful for the animal (MacLachlan, 2005; Karczewski, 2011). The benefit of this mask, and later variations, was a free bolt located in a fixed place—providing precision for the placement of the stun. This bolt would then be driven into the head with a mallet. Although this improved precision of placement, there was still a downside—the force applied to the bolt was inconsistent because it was dependent on the power of the operator. Other challenges were also created by the slaughter masks, including bending of the bolt and often nearly inextricable lodging of the bolt in the cranium (MacLachlan, 2005). Ultimately, the mask devices had varied results in causing insensibility, but they brought forth the key concept of a guided penetrating bolt (Schwarz, 1901; MacLachlan, 2005).

The concurrent advancements in the firearm industry, specifically the development of full metal powder cartridges, led to the development of free bullet killers (Karczewski, 2011). Since these types of devices utilized gunpowder, and not the strength of a human operator, they were capable of delivering a consistent stun. However, the use of a free bullet increased the risk to human and animal bystanders due to the potential for bullet ricochet (MacLachlan, 2005; Karczewski, 2011). Additionally, food safety concerns arose from the potential deposit of the free bullet anywhere in a carcass.

The first PCB device, Behr's Flash Cattle Killer, was developed in 1902 as part of an international contest to develop humane stunning methods. This device was shaped like a pistol and featured a self-retracting bolt that was powered by gunpowder cartridges (Cash and Heiss, 1907; MacLaclan, 2005; Karczewski, 2011). In subsequent years, additional PCB devices were produced—including the CASH stunner in 1907 by Accles and Shelvoke (Karczewski, 2011). Although these PCB devices were capable of delivering an improved stun and presented fewer risks, the widespread adoption of their use took decades. In a survey of European stunning methods, von Mickwitz (1983) reported the use of PCB devices, as well as the poleaxe, puntilla, and free bullet methods. While the PCB was the most used device, older, less effective methods were still widely used. In the 1970s, PCB devices powered by air (pneumatic) instead of cartridges were introduced. These devices were often modified construction nail guns (Karczewski, 2011). The first pneumatic PCB device developed specifically for stunning, the Jarvis USSS-1, was deployed for use in 2003 (Karczewski, 2011). Developments in PCB devices specifically designed for euthanasia have been even more recent. In 2007, the CASH Dispatch Kit was developed to be a single-step euthanasia method that could be used in commercial swine operations. This device featured a pistol-type captive bolt with interchangeable penetrating and nonpenetrating heads (Woods, 2012). Although PCB devices are over 100 yr old, there is still much to be learned regarding their efficacy across multiple animal populations and how existing devices can be modified to become even more effective.

Requirements for Stunning

In the United States, the Humane Methods of Slaughter Act (7 USC 1901) (United States House of Representatives Office of the Law Revision Council, 2021) and the Regulations that enforce it (9 CFR 313) (United States Electronic Code of Federal Regulations, 2021) state "[all livestock animals] are rendered insensible to pain by a single blow or gunshot or an electrical, chemical or other means that is rapid and effective." This law was signed in 1958 and enforcement began in 1960. The law in its current form exists with amendments made in 1978. This law accelerated the need for refinement of stunning methods, especially captive bolt, to increase efficacy and efficiency. Although the implementation of audits by fast-food companies also yielded improvement and refinement to stunning practices (Grandin, 2000). The only exception to this law, regarding preslaughter stunning, is for religious slaughter—most commonly Kosher or Halal slaughter. There are no laws that specifically govern the on-farm euthanasia of livestock in the United States, but societal expectations are that the methods used are at least as humane as those used in the context of preslaughter stunning.

THEORIES OF OPERATION

There are four primary types of captive bolt devices: cartridge-fired penetrating, pneumatic-fired penetrating, cartridge-fired nonpenetrating, and pneumatic-fired nonpenetrating. These can be categorized by class (penetrating and nonpenetrating) and power (cartridge or pneumatic).

Penetrating vs. Nonpenetrating

Both types of the captive bolt—penetrating and nonpenetrating—have roots in the historical methods used to stun animals prior to slaughter: the poleaxe for PCB devices and the sledgehammer for NPCB devices. All PCB devices include a bolt that extends from the device, which is intended to enter through the animal's skull and disrupt brain tissue. There is more variety with NPCB devices though, where the nonpenetrating head can be in different shapes, primarily a mushroom (also called cone shape) or a round (sometimes referred to as flat) shape (Figure 1; adapted from Frontmatec Accles and Shelvoke, 2020). PCB devices are capable of delivering an irreversible stun, where the animal is rendered insensible resulting in death, while NPCB devices may only deliver a reversible stun though this is dependent on the size and developmental age of the animal. For these reasons, the use of NPCB as a euthanasia tool is generally limited to very young or small animals.

Pneumatic vs. Cartridge Fired

Captive bolt devices are powered by either air pressure (pneumatic) or by a powder cartridge. Within the cartridge-fired devices, there are further classifications based on the shape of the device (pistol vs. inline or cylindrical; Figure 2) and how the bolt operates (free-flight vs. self-retracting; Figure 3). The majority of cartridge-fired PCB devices are actuated by a

Figure 1. Examples of nonpenetrating captive bolt head types (CASH Small Animal Tool, Product Code: CPK200); mushroom or cone nonpenetrating head (left) and round or flat nonpenetrating head (right) (adapted from Accles and Shelvoke, 2020).

Figure 2. Examples of inline (top) and pistol (bottom) penetrating captive bolt devices. Inline device: Jarvis Model PAS Type C—0.25R Calber, Super Heavy Duty (Order #: 4144059, Jarvis Corp., Middletown, CT). Pistol device: Jarvis Model PAS Type P—0.25R Caliber Captive Bolt Pistol (Order #: 4144035) with the Long Stunning Rod Nosepiece Assembly (Order #: 3116605).

trigger. However, some alternative, contact-fired devices exist. These alterative, contact-fired devices use physical contact with the animals' heads to actuate the PCB.

The differences in device shape—for cartridge-fired PCBs—are easy to distinguish, as the two types of devices look quite different. To fully identify the differences between the free-flight and self-retracting cartridge-fired PCB device types, it is critical to look at the buffers which line the bolt. Self-retracting devices have buffers that line the full length of the bolt, and the bolt is fully retracted back into the barrel of the device after firing. Free-flight devices do not have buffers that line the full length of the bolt. Instead, these devices generally contain a set of three buffers. The presence of fewer buffers allows for a greater bolt travel distance when using the same bolt length and strength powder cartridge.

FACTORS THAT AFFECT PERFORMANCE

There are many factors that may impact performance, defined as the ability of a PCB device to render an animal insensible and cause subsequent death. These involve physical aspects of the PCB device itself, the operator, and features that are characteristic of the species and type of animal.

Figure 3. Examples of buffer system for free-flight (top) and self-retracting (bottom) penetrating captive bolt devices. Free-flight device: Jarvis Model PAS Type C—0.25R Caliber, Super Heavy Duty (Order #: 4144059, Jarvis Corp., Middletown, CT). Self-retracting device: Jarvis Model PAS—Type P 0.25R Caliber Captive Bolt Pistol (Order #: 4144035, Jarvis Corp.) with the Long Stunning Rod Nosepiece Assembly (Order #: 3116605, Jarvis Corp.).

Nonanimal Factors

The nonanimal factors impacting PCB performance, and ultimately efficacy, are often simpler to manage and fix than the animal factors. This is largely because issues with these factors can be fixed with improved management practices (Grandin, 2002). In a survey of beef slaughter establishments, Grandin (2002) found that damp powder cartridges, poor PCB maintenance, and inexperienced stunner operators not applying the PCB in a correct placement were problems that contributed to issues with rendering animals insensible as well as issues with a return to sensibility. The problems identified by Grandin (2002) were corroborated by the North American Meat Institute (NAMI, 2021) as potential causes of poor PCB stunning outcomes. Additionally, NAMI (2021) described the poor maintenance of the firing pin, poor ergonomics which complicate device handling for pneumatic PCB devices, low air pressure supply to pneumatic devices, and worn cylinder bores for pneumatic devices as other nonanimal factors impairing PCB performance.

In addition to the problems identified through observation of PCB stunning in slaughter establishments which have been detailed above, Gibson et al. (2015) conducted a laboratory study to provide to better understanding of the factors impacting cartridge-fired PCB performance. This study used PCB device metrics to show that when cartridge-fired PCB devices are repeatedly used in a given circumstance, it is important to have multiple devices and to rotate them between groups of animals. This PCB rotation allows for optimal performance, as it allows time for the device to cool and also provides designated device cleaning time. When used for multiple applications within a single session, such as in a large slaughter establishment or a mass depopulation event, PCB devices should be cleaned at least every 500 applications to prevent decreases in performance (Gibson et al., 2015). Captive bolt devices which are used for on-farm euthanasia should be cleaned at the end of the day when the device is used. Regular cleaning also allows for inspection of the bolt, barrel, and buffers—providing the opportunity to identify issues before performance problems arise (Gibson et al., 2015). In addition, wear and damage to the buffers may present a safety risk by limiting the bolt's ability to fully retract into the barrel of the PCB (Gibson et al., 2015).

Ultimately, the selection of a PCB device and the cartridges used with it must involve consideration of the amount of kinetic energy that is provided to the bolt, the bolt penetration depth (the distance the bolt extends from the barrel when fired), and the manufacturer recommendations for maintenance. It is also imperative to select a PCB device, bolt length, and powder cartridge or air supply based on consideration of the specific species and type of animal that will be stunned or euthanized (Gibson et al., 2015).

Animal Factors

There are some general animal factors that impact PCB device performance, including animal behavior (NAMI, 2021) and anatomical features of certain species and types of animals (Grandin, 2002). Indeed, animals that are too excited or agitated are more likely to move their heads during stunning, increasing the chance of failure with a given PCB application (NAMI, 2021). However, this section will primarily focus on the factors associated with certain species and types of animals that present challenges to PCB use. Examples are mature cattle (both bulls and cull cows), small ruminants with extensive horn development, or more exotic animals (e.g., bison and water buffalo). Additionally, while a frontal PCB application site is common across species, the specific device placement on the front of the animal's head varies between species—and in some cases, even between types of animals within species. There are exceptions to this frontal placement for some species or populations within species. One common feature of the frontal PCB placement across all species is that the device should never be placed between the eyes on the same plane as the eyes; the PCB device should never be placed in such a location because that landmark would be too low for the bolt to reliably hit the brain across species.

For small ruminants, there are multiple placements that may be used (Plummer et al., 2018; AVMA, 2020). These placements include descriptions that are not clear and leave potential for the inconsistent placement of PCB devices for these animals (Plummer et al., 2018). Additionally, extensive horn development can present substantial animal welfare risks and challenges for PCB euthanasia. First, the horns themselves may prohibit the correct placement of the PCB device. Second, the horn development and attachment to the skull may increase the total distance the bolt needs to travel through in order to reach the brain (Gibson et al., 2012). Gibson et al. (2012) reported that rams have a thicker skull than ewes, as well as an additional tissue pad above the skull. This tissue pad was thickest in horned rams.

For cattle, there have been well-described difficulties in stunning or euthanizing mature bulls with a PCB device (Grandin, 2002; AABP, 2019; AVMA, 2020) due to the increased skull thickness that is characteristic of these animals. Increased risks to the PCB device operator because of temperament have also been reported (AABP, 2019). Additionally, a distinction between PCB device placement for dairy cattle with a long-face phenotype (such as Holsteins) has been made from the placement for beef cattle. Indeed, a higher PCB placement on the forehead of these cows may increase the likelihood of causing brain damage to regions important for sensibility (Gilliam et al., 2012, 2016, 2018; AABP, 2019; AVMA, 2020). The key difference between these placements is that, instead of placing the PCB device at the intersection of imaginary lines from the lateral canthus of each eye to the base of the opposite horn or poll as one would for beef animals (AVMA, 2020), the PCB device is placed at midline halfway between the top of the poll and a line drawn between the two lateral canthi (Gilliam et al., 2018). An alternative placement known as the poll shot, where the PCB is directly behind the poll and directed toward the nose, has been identified for cattle but is not recommended because of a high risk of hitting the spinal cord and causing paralysis without insensibility (Gregory et al., 2009; AABP, 2019; AVMA, 2020).

One additional animal factor that impacts PCB device performance across all species, swine included, is restraint. When appropriate restraint is utilized, the ability of the animal to move their body, in particular the head, is very limited, allowing for more accurate device placement and increasing PCB success rate. It is important to note that failure to appropriately restrain an animal during euthanasia can lead to severe injury to farm personnel. Appropriate restraint varies given the species, age, and condition of an animal. In swine larger than 12 kg, a snare is most commonly used for restraint before and during PCB application.

INDICATORS OF EFFICACY

Because of the distinction between stunning and euthanasia, as well as single-step and two-step euthanasia methods, discussing efficacy can be complex. With a focus on captive bolt (penetrating and nonpenetrating) as a method of euthanasia, the animal first must be rendered immediately insensible. If this does not occur, then the first threshold (immediate insensibility) has not been met and the method is not appropriate for the situation. If immediate insensibility does occur, then the animal should be monitored for death.

Loss of Sensibility and Commons Signs of Insensibility

There are many common criteria that are used to differentiate sensibility and insensibility. In order to evaluate sensibility and insensibility, a general understanding of these criteria is important. Here, each criterion has been defined so that stakeholders have a *lingua franca* or shared understanding of that vocabulary (Table 2).

With the exception of obvious signs of sensibility, such as righting reflex, the absence of a criterion that is indicative of sensibility does not guarantee insensibility, and the opposite is also true. Additionally, some parameters are not as well understood: they either lack power in discriminating between sensibility and insensibility, require further development and validation, or a combination of those two things (Terlouw et al., 2016).

Criteria that are widely considered to be indicative of sensibility include: standing posture (Atkinson et al., 2013; Verhoeven et al., 2015; Terlouw et al., 2016; AVMA, 2020; NAMI, 2021), righting reflex (Atkinson et al., 2013; Verhoeven et al., 2015; Terlouw et al., 2016; AVMA, 2020; NAMI, 2021), vocalization (Atkinson et al., 2013; Verhoeven et al., 2015; NPB and AASV, 2016; Terlouw et al., 2016; AVMA, 2020; NAMI, 2021), blinking (Verhoeven et al., 2015; Terlouw et al., 2016; AVMA, 2020; NAMI, 2021), eye pursuit (Verhoeven et al., 2015; Terlouw et al., 2016; AVMA,

Table 2. Criteria used to evaluate sensibility and insensibility

Criteria	Definition(s)
Standing posture	Animal remains upright; Inability of an animal to remain in an upright position (Verhoeven et al., 2015) Failure to collapse immediately following a stun (Atkinson et al., 2013)
Vocalization	Voluntary sounds that are made by the animal; needs to be differentiated from any gasping or gagging sounds (Verhoeven et al., 2015)
Blinking	Unprovoked opening and closing (both opening and closure of the eye are required to be considered blinking) (Atkinson et al., 2013)
Eye pursuit/focused eye movements	Involves the following of an object with the eye
Menace test	Also known as the "threat test" Test of the reflex to a nontouch movement near the eye (NAMI, 2021)
Corneal reflex	Testing involves the physical stimulation of the cornea, an eye blink response indicates the reflex is resent (Atkinson et al., 2013; Verhoeven et al., 2015)
Palpebral reflex	Testing involves touching the eyelid for an involuntary response (Terlouw et al., 2016)
Eyelash reflex	Testing involves the physical stimulation of the eyelashes for an involuntary response (Terlouw et al., 2016)
Dazzle response	Testing for the dazzle response involves the shining a bright light at the animal's eye for an involuntary eye blink response (Vogel et al., 2011)
Rhythmic breathing	The regular inhale-exhale cycles; two of these cycles (two full breaths) are considered necessary in order to identify rhythmic breathing (NAMI, 2021)
Full eyeball rotation	Rotation of the eye such that the iris is largely invisible
Nystagmus	Repetitive, uncontrolled movements of the eye, such that the eye appears to be vibrating (NAMI, 2021) These movements are rapid and occur on a lateral oscillation (Atkinson et al., 2013)
Visual evoked responses/potentials	Electrical activity from the brain in response to visual stimulus (Verhoeven et al., 2015). Limited to use in laboratory settings because impractical to test in the field.

2020; NAMI, 2021), and a positive response to the menace test (Terlouw et al., 2016; AVMA, 2020; NAMI, 2021).

Atkinson et al. (2013) described a response to a painful stimulus, the presence of corneal reflex, and rhythmic breathing as being other symptoms of sensibility which present the highest risk to animal welfare following the application of a PCB device. In addition, Atkinson et al. (2013) described the presence of full eyeball rotation and nystagmus to indicate a high-risk relative to animal welfare following the application of a PCB device. Although these symptoms are not necessarily indicative of sensibility as Terlouw et al. (2016) described these as criteria that are not well understood in regard to sensibility at this time.

Criteria that are generally considered to be indicative of insensibility include: the absence of corneal reflex (NPB and AASV, 2016; Terlouw et al., 2016; AVMA, 2020; NAMI, 2021), absence of eyelash reflex (Terlouw et al., 2016; AVMA, 2020; NAMI, 2021), absence of rhythmic breathing (NPB and AASV, 2016; Terlouw et al., 2016; AVMA, 2020; NAMI, 2021), and absence of menace reflex (NAMI, 2021).

An animal is considered insensible if three (Terlouw et al., 2016; AVMA, 2020) or four (NAMI, 2021) out of the aforementioned criteria are present. In addition, the NAMI (2021) describes that an animal that an insensible animal may be transitioning back to sensibility if any of the following criteria are observed: the presence of eyelash reflex, presence of corneal reflex, and presence of rhythmic breathing.

There is no consensus in the literature regarding the presence of full eyeball rotation and nystagmus. Some authors have reported these criteria as high-risk relative to animal welfare if they are present after the application of a PCB device (Atkinson et al., 2013) but others have noted that there is a lack of understanding of their presence as a marker of sensibility in stunned animals (Terlouw et al., 2016). Other criteria that may have implications for sensibility or insensibility, but are not fully characterized at this time include: muscle tone (NPB and AASV, 2016; Terlouw et al., 2016), the absence of clonic and tonic convulsions (Atkinson et al., 2013), response to a painful stimulus (NPB and AASV, 2016; Terlouw et al., 2016), response to nonthreat or nonpainful stimuli (Terlouw et al., 2016), groaning (Atkinson et al., 2013), gasping (Atkinson et al., 2013), head raising (Atkinson et al., 2013), the nondownward positioning of the ears (Atkinson et al., 2013), and the retention of the tongue within the mouth (Atkinson et al., 2013).

Ultimately, if any indicator of sensibility is present, be it based upon a literature consensus or still debated, an additional PCB application should be made immediately to preserve animal welfare (NPB and AASV, 2016; NAMI, 2021).

SWINE

General Considerations for Swine

There is limited literature related to the PCB and NPCB euthanasia of swine. The majority of peer-reviewed scientific publications on the topic at the time of this review were focused on NPCB euthanasia of neonatal (3 d of age or younger) pigs (Casey-Trott et al., 2013, 2014; Grist et al., 2017, 2018a, 2018b). At the time of this review, one peer-reviewed scientific publication exists related to the PCB euthanasia of grower-finisher swine (Anderson et al., 2019) and two on the PCB euthanasia of breeding swine (Anderson et al., 2021; Kramer et al., 2021). In addition, a thesis focuses on the NPCB and PCB euthanasia of six weight classes of swine, from 2 to 200 + kg (Woods, 2012). The specific captive bolt devices, and their respective power sources, used in each study are outlined in Table 3. Other literature includes

Table 3. Description of captive bolt devices[1] used in the swine studies included in this review

Study	Body weight, kg	Captive bolt model and manufacturer	Power source[2]
Woods (2012)	2 to 3	0.25R Caliber CASH Dispatch Kit (Accles and Shelvoke, Suton Coldfield, West Midlands, UK) Nonpenetrating	Pink powder cartridge (1.25 GR)
Grist et al. (2018a)	1.222 ± 0.665 (Mean ± SE)	0.22R Caliber CASH Small Animal Tool (Accles and Shelvoke) Nonpenetrating	1.0 and 1.25 GR cartridges[3]
Casey-Trott et al. (2013)	1.04 ± 0.03 (Mean ± SE) All less than 72 h old	Zephyr-E (Bock Industries, Phillipsburg, PA) Nonpenetrating	115 to 120 psi pneumatic
Grist et al. (2017)	3 to 11	Zephyr EXL (Bock Industries, Phillipsburg, PA) Nonpenetrating	120 psi pneumatic
Grist et al. (2018b)	1.86 ± 0.74 (Mean ± SE)	Zephyr EXL (Bock Industries, Phillipsburg, PA)	120 psi pneumatic
Casey-Trott et al. (2014)	3 to 9	Zephyr-E (Bock Industries, Phillipsburg, PA)	115 to 120 psi pneumatic
Finnie et al. (2003)	15 to 18	Mushroom head captive bolt pistol[4] (Karl Schermer & Co, Karlsruhe, Germany)	Schermer No 17 charge
Woods (2012)	7.5 to 10	0.25R CASH Dispatch Kit (Accles and Shelvoke, Suton Coldfield, West Midlands, UK) Nonpenetrating	Pink powder cartridge (1.25 GR)
Woods (2012)	15 to 20	0.25R Caliber CASH Dispatch Kit (Accles and Shelvoke, Suton Coldfield, West Midlands, UK) Penetrating, Short bolt	Yellow powder cartridge (2 GR)
Woods (2012)	30 to 40	0.25R CASH Dispatch Kit (Accles and Shelvoke, Suton Coldfield, West Midlands, UK) Penetrating, Short bolt	Yellow powdercartridge (2 GR)
Woods (2012)	100 to 120	0.25R CASH Dispatch Kit (Accles and Shelvoke, Suton Coldfield, West Midlands, UK) Penetrating, Medium bolt	Blue powder cartridge (3 GR)
Anderson et al. (2019)	136	Jarvis PAS-Type P 0.25R Caliber Captive Bolt Pistol (Order #: 4144035, Jarvis Corp., Middletown, CT) Penetrating, Medium stunning rod	Blue powder cartridge (3.0 GR)
Anderson et al. (2021)	≥200	Jarvis PAS-Type P 0.25R Caliber Captive Bolt Pistol (Order #: 4144035, Jarvis Corp., Middletown, CT) Penetrating, Long stunning rod	Orange powder cartridge (3.5 GR)
Woods (2012)	≥200 (Visually estimated)	0.25R Caliber CASH Dispatch Kit (Accles and Shelvoke, Suton Coldfield, West Midlands, UK) Penetrating, extended bolt	Orangepowdercartridge (3.5 GR) Black powder cartridge (4.0 GR)[5]
Kramer et al. (2021)[6]	≥200	Type-P (Pistol): Jarvis PAS-Type P 0.25R Caliber Super Heavy Duty Captive Bolt Pistol (Order #: 4144133) Jarvis Corp., Middletown, CT) Penetrating, Extended bolt Type-C (Inline): Jarvis PAS-Type C 0.25R Caliber Super Heavy Duty Inline Captive Bolt (Order #: 4144059) Jarvis Corp., Middletown, CT) Penetrating, Extended bolt	Type-P (Pistol):Blackpowdercartridge (4.0 GR) Type-C (Inline): Red powder cartridge (6.0 GR)

[1]The authors of this review are not responsible for discrepancies in cartridge size between original articles and manufacturer information.
[2]Power source information provided is based upon the information provided in each original manuscript.
[3]Initially, 1.25 GR cartridges were used, but due to damage to piglets and excessive wear to the nonpenetrating captive bolt, 1.0 GR cartridges were used.
[4]Caliber not described.
[5]In the on-farm trials, the black (4.0 GR) cartridge "was used on the larger pigs within [the] weight class at the discretion of the researcher based on visual assessment of weight." Manufacturer recommendations list that a cartridge of 3.5 GR is the maximum power source to be used with this device (Accles and Shelvoke, 2020).
[6]Complete device information is not included within this article, information provided via personal communication (S. Kramer, Animal Plant and Health Inspection Service, United States Department of Agriculture, Riverdale, MD, USA).

industry guidance documents (HSA, 2016; NPB and AASV, 2016; AVMA, 2020), and portions of two peer-reviewed scientific opinions from European Food Safety Authority (EFSA, 2004, 2020). The limited literature, paired with the challenges to be presented in this section, demonstrates a clear need for further research regarding PCB euthanasia for swine.

Pigs are categorized as the most difficult animals to stun with a PCB (HSA, 2016). This is especially true for mature sows and boars, where a bony ridge along the center of the forehead can prevent the bolt from reaching the brain (HSA, 2016). To this extent, an animal welfare concern identified by the EFSA Panel on Animal Health and Welfare (EFSA, 2004) was that PCB may not be an effective means of euthanasia for mature sows and boars. In a more recent publication, the EFSA Panel on Animal Health and Welfare (EFSA, 2020) also reported that large boars are more difficult to stun with a PCB than other classes of swine due to well-developed sinus cavities and the location of the brain deeper within the skull. The use of an NPCB can also present challenges when euthanizing pigs, as it is most effective prior to the development and hardening of the frontal bones (AVMA, 2020).

Neonatal Swine (3 d and younger)

NPCB is considered an "acceptable" method of euthanasia for suckling swine before the frontal bones are fully developed (NPB and AASV, 2016; AVMA, 2020). NPCB is a good alternative to manual blunt force trauma for neonatal animals, as this less esthetically disturbing method produces a more consistent blow to the head (NPB and AASV, 2016; AVMA, 2020). Additionally, the use of an NPCB device over manually applied blunt force trauma for the euthanasia of neonatal swine may lessen the negative emotional experience of the person tasked with the procedure. Research regarding the euthanasia of neonatal swine with NPCB devices can be grouped into two categories: studies that utilized a cartridge-fired NPCB (Woods, 2012; Grist et al., 2018a) and those studies that utilized a pneumatic-fired NPCB (Casey-Trott et al., 2013; Grist et al., 2017, 2018b).

In evaluations of cartridge-fired NPCB devices as a single-step euthanasia method, it was found that the method is 100% effective for euthanizing neonatal piglets (Woods, 2012; Grist et al., 2018a) with a single application. Woods (2012) did a two-step evaluation of the CASH Dispatch Kit, a pistol-type device, equipped with the nonpenetrating head, and 1.25 GR powder cartridges with a frontal application for swine weighing 2 to 3 kg: first with anesthetized animals and then with live conscious animals in on-farm field trials. Grist et al. (2018a) evaluated the CASH small animal tool, an inline-type device, in an on-farm field trial using 1.25 and 1.0 GR powder cartridges; two different cartridge strengths were evaluated because the heavier (1.25 GR) cartridge caused extensive wear to the device and greater damage to the animals. Both Woods (2012) and Grist et al. (2018a) reported noticeable skull displacement, Woods (2012) described an indentation that was present in the skull of all animals that was in the shape of the NPCB head—like a cookie-cutter indentation. Similarly, Grist (2018a) described a similar finding, where all animals had a depressed fracture in the shape of the NPCB head, with subdural hematoma at the site as well. Additionally, Grist et al. (2018a) reported bone shards associated with these fractures of the parietal plate into the parietal lobe of the brain. The time to last movement, including clonic movements, following the application of an NPCB has been reported to be as short as 86.95 s (Grist et al., 2018a) and as long as 152.1 s (Woods, 2012). Grist et al. (2018a) observed a shorter time to last movement when the higher grain cartridge was used. These findings indicate that movement is to be expected when using an NPCB device to euthanize neonatal piglets. Beyond the different PCB devices used, there are some other key differences to recognize between these studies. Woods (2012) used heavier animals than Grist et al. (2018a) did (2 to 3 kg and 1.2 kg, respectively). In addition, brain injury and hemorrhage were assessed by both Woods (2012) and Grist et al. (2018a), although the methods for the assessment and reporting of results vary. Woods (2012) found damage in the cerebral cortex, thalamus, cerebellum, pons, and medulla; a three-point scoring system was used, but it is not possible to distinguish the level of damage for any of these regions because results are reported in combination with some results from heavier, nursery pigs. Grist et al. (2018a) used a four-point scoring system to assess damage in the frontal, parietal, and occipital lobes of the brain but summed damage scores prior to reporting results so the regions damaged and the extent of that damage for each region is unknown. In regard to hemorrhage, the metric for scoring was much more similar, where the presence or absence of hemorrhage was recorded. Woods (2012) found evidence of visual hemorrhage in all regions assessed (cerebral cortex, cerebellum, thalamus, pons, and medulla) while Grist et al. (2018a) evaluated the thalamus, midbrain, pons, and medulla for hemorrhage, but only reported the sums and averages of hemorrhage scores. Lastly, agonal gasping was reported for 4% (8 of 202) animals in the study by Grist et al. (2018a), both prior to and after 3 min post NPCB application.

In evaluations of pneumatic-fired NPCB devices as a single-step method of euthanasia, Casey-Trott et al. (2013) and Grist et al. (2017, 2018b) evaluated the efficacy of the device to cause immediate insensibility and, ultimately, death. These studies occurred in a succession such that the results of one informed the next: the work done by Casey-Trott et al. (2013) used the Zephyr-E, a version of a rabbit stunner that had been modified for use in euthanasia events; Grist et al. (2017) used the Zephyr-EXL, a device that had been modified following the results of the work by Casey-Trott et al. (2013) to operate at a higher velocity and had a higher pressure in order to achieve insensibility outcomes with only a single application. The work by Grist et al. (2018b) was the field trial to follow up the Grist et al. (2017) work. Casey-Trott et al. (2013) used a three-stun method: the NPCB was first applied to the frontal bone twice (in rapid succession) and subsequently immediately applied to the back of the skull or behind the ear. Grist et al. (2017, 2018a) used a single application of the NPCB device with a placement consistent with the description of the frontal placement described by the NPB and AASV (2016). Casey-Trott et al. (2013) found that 100% of animals were immediately rendered insensible and that the NPCB applications resulted in death for 94% of animals (94 of 100); 4 animals did not achieve cardiac arrest within 15 min post NPCB application and were exsanguinated and another 2 displayed convulsions and were administered an anesthetic overdose. Grist et al. (2017) found that all (60 of 60) anesthetized animals were immediately rendered insensible after a single application of the NPCB device and that 59 of those animals were killed from the application. The animal that was not determined to be killed demonstrated visual evoked potentials past the 360 s cutoff point, although no other signs of sensibility were present; this was the first animal in the study and its head was supported in a foam cushion, so the authors laid each subsequent piglet on a hard surface. This finding has practical implications. When using an NPCB device to euthanize piglets, the animal should be supported on a hard surface, such as a tabletop, to ensure the best likelihood of positive outcomes. In on-farm field trials, Grist et al. (2018b) reported that all (207 of 207) animals were immediately rendered insensible following a single NPCB application, but that 1 animal received an additional application due to agonal gasping 10 min post-application. In the field trials at operational speed, Grist et al. (2018b) reported that all (106 of 106) animals were immediately rendered insensible with a single NPCB application. Grist et al. (2018b) reported agonal gasping in the first part of their field trial for 16% (34 of 207) of animals, but no other signs of sensibility were present, indicating that agonal gasping may be somewhat common following NPCB application in piglets, although this phenomenon is not well understood at this time.

Preweaning (3 d–3 to 4 wk of Age) and Nursery (3 to 4 wk of age, 31 kg) Swine

NPCB is approved for use as a single-step method of euthanasia in preweaning piglets and as a two-step method in nursery age pigs (NPB and AASV, 2016; AVMA, 2020). Indeed, it is required that a secondary method be used in conjunction with NPCB for nursery-age pigs, as the concussive impact results in an immediate loss of sensibility but may not achieve death (AVMA, 2020). For nursery swine, PCB is also a method of euthanasia that is "acceptable with conditions"; although a secondary step is not required, it is critical to ensure that appropriate restraint is used and that the animal is monitored for signs of sensibility until death is achieved (AVMA, 2020).

Casey-Trott et al. (2014) evaluated the efficacy of a pneumatic NPCB device for the euthanasia of suckling and weaned pigs weighing 3 to 9 kg (across four weight classes: 2.5 to 3.9 kg, 4.0 to 5.9 kg, 6.0 to 7.9 kg, and 8.0 to 10.2 kg), using a two-stun method where the NPCB was applied twice in rapid succession to the frontal bone. Following the NPCB application, all animals were assessed for sensibility using the indicators of corneal reflex, pupillary light reflex, jaw tone, and response to painful stimuli. Cardiac arrest, indicated by a lack of detectable heartbeat with auscultation or palpation, was the criteria for the achievement of death. Of the 150 animals that received an NPCB application, all but two were rendered immediately insensible and insensibility was maintained until cardiac arrest occurred. One of the two remaining animals responded to the corneal reflex test with an eye closure event and received a second NPCB application which immediately eliminated the eye closure response and rendered the animal insensible (Casey-Trott et al., 2014). The second animal was rendered immediately insensible but began to transition from gasping to rhythmic breathing, so the investigators applied two additional NPCB applications behind each ear and the animal was once again rendered insensible (Casey-Trott et al., 2014). Upon postmortem evaluation, it was revealed that skull fracture was evident in all animals, but one animal did not have a displacement of the brain resulting from the fracture.

In an early attempt to understand the impact of an NPCB device on nursery pigs, Finnie et al. (2003) studied the traumatic brain injury (**TBI**) resulting from the application of a mushroom head NPCB device in 15 to 18 kg anesthetized pigs. In addition to assessing the TBI resulting from this NPCB application, the findings were also compared to those from a similarly designed study in lambs. Finnie et al. (2003) reported that the inner table of the skull was intact in six of six animals, indicating a closed head injury, while the outer table of the skull was fractured in two of these six animals. Subarachnoid hemorrhage was present near the brainstem and the base of the brain for two of the six animals, but no evidence of impact contusion was present in the brains of any of the animals (zero of six; Finnie et al., 2003). Microscopic evaluation of the brains revealed the axonal injury, as indicated by a biological marker (amyloid precursor protein), in the cerebral cortex, cerebellum, and brainstem in four of six animals (Finnie et al., 2003). Ultimately, when compared with the similar work in lambs, the brain damage produced by the NPCB in pigs was substantially less (Finnie et al., 2003).

Woods (2012) also evaluated the efficacy of a pistol-type NPCB with a frontal application as a single-step euthanasia method for nursery swine weighing 7.5 to 10 kg. As with the PCB work in heavier nursery pigs, this was done in two stages: first with anesthetized animals and then with live-conscious animals in on-farm field trials. In the first, anesthetized, stage, six of six animals were effectively euthanized (Woods, 2012). Same as the work done with the heavier nursery pigs euthanized with a PCB device, Woods (2012) evaluated the presence of visible hemorrhage in the cerebral cortex, cerebellum, thalamus, pons, and medulla. Visible evidence of hemorrhage was present in all structures assessed (cerebral cortex, cerebellum, thalamus, pons, and medulla) for all six animals in this weight class (Woods, 2012). Additionally, the six animals in this weight class all had evidence of a "cookie-cutter" effect on the skull, where the bone was depressed in the shape of the nonpenetrating head but the skin was fully intact (Woods, 2012). Woods (2012) also evaluated TBI of the six animals in this weight class using a three-point scoring scheme (0—grossly normal, 1—some abnormalities, 2—grossly abnormal/unrecognizable) and found that all evaluated structures (cerebral cortex, thalamus, cerebellum, pons, and medulla) had at least some abnormalities. The level of TBI for each structure was reported along with the TBI data for lighter animals as well, so it is only possible to distinguish that the cerebral cortex of the brain of all six of the pigs in this lighter nursery class had damage to the extent that the structure was grossly abnormal (score of 2). In the on-farm field trials of the second stage, 30 of 30 pigs were immediately rendered insensible (immediate collapse and lack of corneal reflex) and subsequently achieved death (cessation of cardiac and respiratory function within 10 min) indicating effective euthanasia following the application of an NPCB (Woods, 2012).

Woods (2012) evaluated the efficacy of a pistol-type PCB with a frontal application as a single-step euthanasia method for nursery swine weighing 15 to 20 kg. This was done in two stages, first on anesthetized animals and then with live-conscious animals in on-farm trials. In both stages, effective euthanasia was defined as the cessation of cardiac and respiratory activity—ultimately death—within 10 min of the PCB application. In the anesthetized stage, six of six pigs were effectively euthanized (Woods, 2012). Beyond the assessment of death outcomes for the animals enrolled in this stage, Woods (2012) also assessed the brains for physical penetration of the bolt and visible hemorrhage of the brain in the cerebral cortex, thalamus, cerebellum, pons, and medulla (Woods, 2012). Physical penetration of the brain in a frontal location for all six animals in this weight class and hemorrhage was present in all structures assessed for all six animals as well. The subsequent, on-farm trials with live-conscious animals, yielded similar results, where all animals (30 of 30 animals) were immediately rendered insensible (immediate collapse and lack of corneal reflex) and effectively euthanized following a single application of a pistol-type PCB (Woods, 2012). A snare was used to restrain all 30 animals in the on-farm trials.

Grower-Finisher Swine (31+ kg)

PCB is considered to be a method of euthanasia that is "acceptable with conditions" for grower-finisher swine by the American Veterinary Medical Association (AVMA, 2020). For the swine of this class, it is important to monitor animals until death has been confirmed, but there are no known difficulties that may prevent effective euthanasia. The method is also approved for use in this class of swine by the National Pork Board and the American Association of Swine Veterinarians (NPB and AASV, 2016). When using a PCB to euthanize growing pigs, the Humane Slaughter Association (**HSA**) recommends that the most powerful cartridge that is compatible with a given PCB device be used and that a PCB application is immediately followed by pithing or exsanguination to ensure death (HSA, 2016). Across all guidance documents, a similar frontal PCB placement is described; however, the specific placement of the device on the front of the pigs' head varies across guidelines. The nuances of these placement descriptions can be found in Table 1. In addition to these differences in the specific location of the PCB in the frontal placement, two alternative placements have been identified: temporal and behind the ear (AVMA, 2013). Although there are no known challenges that prevent the efficacy of PCB as a euthanasia method in the frontal placement with grower-finisher swine, these alternative placements would be valuable in situations where it is difficult to access and restrain a pig for proper application in the frontal placement. Because there has not been scientific validation of the temporal or behind ear placement as effective euthanasia methods for grower-finisher swine, the AVMA has recently specified that those placements are only approved for use with gunshot (AVMA, 2020).

Among current literature regarding the PCB euthanasia of grower-finisher swine, there is a consensus that the frontal placement is appropriate and effective (Woods, 2012; Anderson et al., 2019). Woods (2012) evaluated the efficacy of a pistol-type PCB with a frontal application as a single-step euthanasia method for two weight classes of grower-finisher swine (30 to 40 kg, 100 to 120 kg) in two stages: first on anesthetized animals and then with live animals in on-farm field trials. In both stages, effective euthanasia was defined by the cessation of cardiac and respiratory activity—and ultimately death—within 10 min of the PCB application. In the first stage with the anesthetized stage, six of six pigs in each of the weight class (12 animals total) were effectively euthanized (Woods, 2012). In addition to assessing death outcomes for animals enrolled in the first stage, Woods (2012) also evaluated hemorrhage of the brain in the cerebral cortex, thalamus, cerebellum, pons, and medulla. Visible hemorrhage was present in five structures (cerebral cortex, thalamus, cerebellum, pons, and medulla) for all 12 animals that were part of this portion of the study (Woods, 2012). The subsequent, on-farm trials with live-conscious animals, yielded similar results, where all animals in both weight classes (30 of 30 animals per weight class, 60 animals total) were immediately rendered insensible (immediate collapse and lack of corneal reflex) and effectively euthanized (death achieved via cessation of cardiac and respiratory activity within 10 min) following a single application of a pistol-type PCB (Woods, 2012). A snare was used to restrain all 30 animals in each weight class (60 animals total) in the on-farm trials.

Anderson et al. (2019) evaluated tissue depth measurements, brain area, and bolt-brain contact associated with the common frontal PCB placement and the alternative PCB placement that has been identified with a pistol-type PCB on cadaver heads from market hogs (estimated BW: 136 kg). The authors concluded that the frontal placement appeared to be more reliable than the behind ear placement due to less tissue thickness (soft tissue thickness, cranial thickness, and total tissue thickness) and a larger target area (Anderson et al., 2019).

Woods (2012) found that there was a penetration of the brain of all anesthetized grower-finisher swine, Anderson et al. (2019) had similar findings where bolt-brain contact was observed in all heads (11 of 11) that received a PCB application in the frontal placement. Specifically, Woods (2012) noted visible penetration of the brain in a frontal location for five of six animals in the 30 to 40 kg weight class and penetration of the brain in a parietal location for the remaining animal of this size. Visible penetration of the brain was also observed in a frontal location for all (six of six) animals in the 100 to 120 kg grouping (Woods, 2012). The bolt–brain contact observed in heads with a behind ear PCB application (8 of 12) was less than in those that received a frontal PCB application (Anderson et al., 2019). Collectively, these findings indicate that the pistol-type PCB devices used in the aforementioned studies are likely to reach the brain from the frontal placement of grower-finisher swine.

As swine age, the likelihood of failure with PCB devices increases. Lambooy et al. (1983) found the average maximum force necessary to penetrate pig skulls from 100 kg BW animals was 32.7 ± 8.8 kg/mm^2. However, in order to ensure penetration at a 99.8% efficacy, the maximum force needed would be 59.1 kg/mm^2. This maximum force for ensuring a high level of efficacy was greater than the maximum force produced by PCB devices from three captive bolt manufacturers at that time, which ranged from 49.1 to 56.0 kg/mm^2 (Lambooy et al., 1983). Although there have been improvements in PCB devices in the time since that study, there is still room for future improvements to increase the likelihood of successful PCB applications and ultimately successful euthanasia for swine as they mature.

Breeding Swine

PCB is considered a method of euthanasia that is "acceptable with conditions" for swine of this class by the AVMA, although it is described that the death cannot be assured in breeding swine because of the expansive frontal sinuses characteristic of mature sows and boars which are not found in younger animals (AVMA, 2020). With sows and boars, the AVMA recognized that there may be a need for the deployment of secondary euthanasia steps—such as a second PCB application, pithing, or exsanguination—and that monitoring an animal until death is achieved is of critical importance (AVMA, 2020). The method is also approved for use in this class of swine by the NPB and AASV (2016), although it is noted that a secondary step may be necessary to ensure death when a PCB is used on mature sows and boars due to the increased skull thickness (NPB and AASV, 2016). An animal welfare concern with mature sows and boars is that PCB may not be an effective means of euthanasia for these animals (EFSA, 2004). More recently, the EFSA Panel on Animal Health and Welfare reported that large boars are more difficult to stun with a PCB than other classes of swine due to well-developed sinus cavities and the location of the brain deeper within the skull (EFSA, 2020). Across all industry guidance and scientific opinions, a frontal PCB placement is described. However, there are differences in the specific placement of the device on the pigs' heads between guidelines. Additionally, some sources recommend a different frontal PCB placement that is higher above the eyes for mature, breeding swine than for grower-finisher swine (Woods et al., 2010; EFSA, 2020).

An overview of these descriptions can be found in Table 4. In addition, two alternative placements—temporal and behind the ear—may be of value and important for breeding swine because of the challenges that have been identified with the frontal placement for these animals (EFSA, 2004, 2020; HSA, 2016; AVMA, 2020). These alternative placements were highlighted in the 2013 AVMA Euthanasia guidelines (AVMA, 2013), but recent updates have indicated that they are intended for use with gunshot only (AVMA, 2020). Despite this, they may serve as valid placements for the PCB euthanasia of breeding swine, however, it is critical that rigorous validation studies occur before they are used in practice.

Anderson et al. (2021) evaluated tissue depth measurements, brain area, brain contact plane, and brain damage associated with the frontal, temporal, and behind ear PCB placements on cadaver heads from mature sows and boars (BW > 200 kg). The authors concluded that the frontal placement appeared to be the most reliable with the PCB device used due to the least total tissue thickness, greatest potential target area, and high prevalence of brain damage. Because cadaver heads, not live animals, were used in this study the efficacy resulting from a PCB application could not be assessed.

Woods (2012) and Kramer et al. (2021) both evaluated the efficacy of euthanasia with PCB devices for breeding swine. In contrast with the Anderson et al. (2021) study, each of these studies was able to assess efficacy because live animals were used. Woods (2012) focused solely on the efficacy of a pistol-type PCB device in the frontal placement as a single-step euthanasia method for animals visually estimated to weigh more than 200 kg. This evaluation was performed in two stages: first on anesthetized animals and then on-farm with live animals. In the anesthetized stage, five of six sows were effectively euthanized (defined by the cessation of cardiac and respiratory activity within 10 min post PCB application) and three of six boars were effectively euthanized following the application of a pistol-type PCB (Woods, 2012). In the subsequent on-farm, live trials, 28 of 30 sows and 25 of 30 boars were rendered insensible immediately following a single PCB application and death (cessation of cardiac and respiratory activity) occurred within 10 min of the PCB application (Woods, 2012). It is important to recognize the importance of restraint in effective euthanasia. Woods (2012) reported ineffective restraint (no snare used) as a potential reason for the high level of sensibility following a PCB application to boars. A snare was used to restrain all 30 sows and 10 of 30 boars; the use of a snare was optional for the first 20 boars that were enrolled by Woods (2012) and was required for all animals thereafter. Criteria for insensibility included an immediate collapse and no presence of involuntary blinking when the cornea was touched. If neither of these occurred, then the PCB

Table 4. Description of penetrating captive bolt placements across guidelines for swine

	Frontal	Temporal	Behind ear
American Veterinary Medical Association (AVMA) (2013)	Center of the forehead slightly above a line drawn between the eyes. Bolt or bullet directed toward the spinal canal.	Slightly anterior and below the ear.	Behind the ear and toward the opposite eye.
AVMA (2020)	Center of the forehead slightly above a line drawn between the eyes. Bolt or bullet directed toward the spinal canal. May be used for both PCB and gunshot.	Slightly anterior and below the ear. Gunshot only.	Behind the ear and toward the opposite eye. Gunshot only.
National Pork Board—American Association of Swine Veterinarians (NPB-AASV) (2016)	At the midline of the forehead, 1.27 cm above eye level (even with the eyebrows). The PCB should be placed very firmly against the skull, aimed at the brain and directed toward the tail.	Not mentioned.	The bullet should enter the skull from behind the ear aiming toward the opposite eye. Alternative for gunshot only.
Humane Slaughter Association (HSA) (2016)	On the midline of the forehead, aiming toward the tail, 20 mm above eye-level.	Not mentioned.	Not mentioned.
North American Meat Institute (NAMI) (2021)	Market weight: 2.54 cm above the eyebrow, in the middle of the forehead. Mature sows and boars: 3 to 4 cm above the eyebrow. Mature pigs with an exaggerated skull may require a slightly lower (1 cm) target.	Not mentioned.	Not mentioned.
European Food Safety Authority (EFSA) (2004)	Placed perpendicular to the surface of the frontal bone.	Not mentioned.	Not mentioned.
EFSA (2020)	Placed 1 to 2 cm above the eyes and aimed toward the tail. Boars and large sows: off-center placement with a higher (3 to 4 cm above the eyes) placement.	Not mentioned.	Not mentioned.

was applied a second time. It is important to recognize that a common indicator of sensibility—the presence of rhythmic breathing (two full inhale–exhale cycles—the movement of the ribs in and out twice, NAMI, 2021)—was not included as a reason for a second PCB application by Woods (2012). It is unclear if an immediate second shot would have been required for two animals where respiration post-application was observed but no eyeblink response was reported (Woods, 2012). Kramer et al. (2021) focused on the efficacy of euthanasia with two PCB types (pistol and inline) at the temporal and behind ear placements for live, mature swine. Similar to the Woods (2012) study, this was performed in two stages: first on anesthetized animals and then on live-conscious animals. In the first stage, death was achieved within 10 min of PCB application for three of three anesthetized sows with the inline-frontal, inline-temporal, inline-behind ear, and pistol-behind ear device-placement combinations; at least one of the three animals was not effectively euthanized with the pistol-frontal and pistol-temporal device-placement combinations (Kramer et al., 2021). Effective euthanasia with death occurring within 10 min of the PCB application occurred for three of three anesthetized boars with the inline-frontal and inline-behind ear device-placement combinations; at least one of three boars did not achieve death following a PCB application with the following device-placement combinations: inline-temporal, pistol-frontal, pistol-temporal, and pistol-behind ear (Kramer et al., 2021). The findings of Woods (2012) and Kramer et al. (2021) indicate that the pistol-type PCB applied in the frontal placement may not be an effective means of euthanasia for mature breeding swine.

One important distinction between the Kramer et al. (2021) and Woods (2012) studies is that in Kramer et al. (2021) a placement-device combination was required to be 95% effective in euthanizing anesthetized animals to be included in testing with live-conscious animals, there was no such requirement in the work done by Woods (2012). Specifically, Kramer et al. (2021) required death, defined by the cessation of cardiac and respiratory activity within 10 min of the PCB application, and because three animals were used to evaluate each device-placement combination, all had to achieve death for the combination to be evaluated in the second stage. In the second, live-conscious, stage, Kramer et al. (2021) reported that all device-placement combinations were evaluated (sows: inline-frontal, inline-temporal, inline-behind ear, pistol-behind ear; boars: inline-frontal, inline-behind ear) were effective (seven of seven animals effectively euthanized). All animals were restrained with a snare for PCB application. For this group of animals, the authors did not report checking for an instantaneous loss of sensibility—an important criterion of PCB euthanasia and another key difference between Kramer et al. (2021) and Woods (2012). The failure to check for an instantaneous sense of sensibility has the potential to severely compromise animal welfare. Additional PCB applications were required in order for three animals in the live-conscious stage to be rendered insensible. This occurred with the following device-placement combinations: inline-behind ear, inline-temporal, and behind ear pistol; these additional PCB applications were required due to human error related to the PCB placement during the initial application (personal communication, S. Moeller, The Ohio State University, Columbus, OH). The need for additional PCB applications highlights a need for the refinement of these placements and a critical assessment of insensibility in future work in this area.

Although the findings of both Woods (2012) and Kramer et al. (2021) suggested that the frontal placement with a pistol-type PCB may not be sufficient to euthanize sows and boars, hemorrhage was observed following a frontal PCB application by Woods (2012) and Kramer et al. (2021). Woods (2012) assessed the visual presence of hemorrhage in five regions of the brain (cerebral cortex, thalamus, cerebellum, pons, and medulla) in the anesthetized stage and observed hemorrhage in the thalamus, cerebellum, and medulla for the 8 (of 12) animals that were effectively euthanized with a single PCB application. Kramer et al. (2021) assessed the visual presence of hemorrhage in the frontal, parietal, temporal, and occipital regions of the brains of all animals enrolled in their study (stages one and two); hemorrhage was scored on a two-point system (0 = no hemorrhage and 1 = hemorrhage) and scores were summed prior to analysis. The summation of hemorrhage scores and not reporting hemorrhage data for each of the four regions prevents the comparison of the findings to those of Woods (2012). Of the two PCB types evaluated by Kramer et al. (2021), the inline device yielded higher average hemorrhage than the pistol-type device in the temporal placement, average hemorrhage scores were not different between PCB types at the frontal or behind ear placements. Of the three placements evaluated by Kramer et al. (2021) the pistol-type PCB resulted in a higher average hemorrhage score in the behind ear placement than the temporal placement, but the average hemorrhage scores at either of those locations did not differ from that of the frontal placement. Of the three placements evaluated by Kramer et al. (2021), there was no difference in average hemorrhage score between placements with the inline-type PCB.

All three studies (Woods, 2012; Anderson et al., 2021; Kramer et al., 2021) evaluated physical damage to the brain, while Woods (2012) and Kramer et al. (2021) also evaluated hemorrhage. Of the eight animals that were effectively euthanized in the anesthetized stage of the work done by Woods (2012), seven had physical penetration of the brain in the frontal location and one had physical penetration of the brain in the occipital location. Of the four animals that were not effectively euthanized in the anesthetized stage of the work done by Woods (2012), there was no evidence of physical penetration of the brain for two animals, one animal had a penetration of the brain in the frontal location and the other animal had a penetration of the brain in the occipital location. Kramer et al. (2021) assessed physical damage to the brains of all animals included in both stages with a TBI scoring system (0 = grossly normal, 1 = some abnormalities, 3 = grossly abnormal or unrecognizable) for the following structures: cerebral cortex, thalamus, hypothalamus, cerebellum, pons, and brainstem. Injury scores were summed prior to analysis. The summation of TBI scores and not reporting TBI data for each of the six structures is a limitation of the work done by Kramer et al. (2021) because relationships between euthanasia outcomes and damage to certain brain structures cannot be assessed. When using the pistol-type PCB, Kramer et al. (2021) found that the average TBI score was higher at the behind ear placement than at the frontal or behind ear placements, when using the inline-type PCB no difference was noted in average TBI score between placements. Of the three PCB placements evaluated by Kramer et al. (2021), the average TBI score in the frontal placement was greater from the inline-type PCB than the pistol-type PCB. There was no difference in the TBI score produced from the different device types in the temporal or behind ear placements. Anderson et al. (2021) assessed the presence of visual damage to the following regions of the brain: frontal lobe, parietal lobe, temporal lobe, occipital lobe, corpus callosum, diencephalon, mesencephalon, brainstem, and cerebellum. The regions of the brain assessed for each PCB placement were dependent upon the regions of the brain that were visible in the exposed cross-section of each head. In addition, overall brain damage—indicating damage to one or more regions of the brain was also determined for each head. Although statistical comparisons for overall brain damage were not made by Anderson et al. (2021), a high prevalence of brain damage was observed in the frontal placement, in contrast with the findings of Kramer et al. (2021) regarding brain damage with the pistol-type PCB. These conflicting findings highlight the need for further research, specifically to determine if a more powerful PCB device would be effective.

CONCLUSIONS

The preslaughter stunning of animals is a long-standing practice, with many developments and improvements that have continued since the early 1900s. More recently, there has been an increased focus on the use of captive bolt devices for on-farm euthanasia. During the same period, several criteria have been defined and validated as markers of sensibility or insensibility. Yet, uncertainty remains regarding the exact moment when an animal irreversibly loses sensibility. NPCB devices have been successfully validated as a single-step method of euthanasia for neonatal and preweaning swine, and a two-step method of euthanasia for nursery swine. Additionally, PCB has been identified as a successful single-step euthanasia method for nursery and market swine. However, the use of PCB devices for mature breeding sows and boars still requires further investigation. Selecting PCB devices with longer bolt reach and the frontal placement of PCB applications with effective restraint will reduce the risk of PCB euthanasia failures for mature breeding sows and boars.

Conflict of interest statement

The authors report no real or perceived conflicts of interest with the content of this publication.

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