The advantages and disadvantages of electrical and CO_2 stunning in relation to animal welfare and meat quality

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Summary

The two most common stunning methods for pigs both in Denmark and in foreign countries are electrical stunning and CO_2 stunning. Both methods have advantages and disadvantages. In particular, the pre-stunning handling, which significantly affects both animal welfare and meat quality, is different between the two methods. Prior to electrical stunning, pigs are isolated and restrained. At high slaughter capacity (number of pigs slaughtered per hour), the pigs are usually led down a raceway and into a restrainer. This requires contact between the slaughterhouse staff and the pigs, which can increase the risk of rough handling, including repeated use of paddles, boards and electric prodder, thus inducing stress for the pigs. The development in CO_2 stunning for the last decades has improved both meat quality and animal welfare. The greatest achievement is the possibility of stunning pigs in groups resulting in a gentler handling prior to stunning. Some pigs, however, react to the gas with increased respiration, vocalisation, and flight reactions in the few seconds before becoming unconscious. Oppositely, electrical stunning leads to an instant loss of consciousness, which is an advantage from an animal welfare standpoint. However, electrical stunning increases the risk of an ineffective stunning in comparison to CO_2 stunning where the risk is minimal. CO_2 stunning is approximately twice as expensive in capital and operation cost compared to automatic electric stunning. Generally, the CO_2 stunning provides better working conditions for the slaughterhouse staff compared to electrical stunning. A summary of the advantages and disadvantages of electrical stunning and CO_2 stunning can be seen in Table 1.

Table 1. Advantages and disadvantages of electrical and CO_2 stunning.

Stunning methods	Advantages	Disadvantages
Electrical stunning	Immediate loss of consciousness. A study confirms that animals do not feel pain during the inducing of stunning (Leach et al., 1980).	Regardless of slaughter capacity, pigs are isolated and restrained prior to application of the electric tongs. During high capacity slaughter, the pigs are also driven to a restrainer, which can stress the pigs.
	Manual electrical stunning requires a small capital investment in equipment (20,000-40,000 DKK). An automated electric system (e.g., MIDAS) is more expensive, but still only half as expensive in operation compared to a CO_2 stunning system.	More contact between slaughterhouse workers and the pigs, which can induce stress for the pigs.
		Even if the amperage and current are adjusted according to the recommendations, there is a risk of ineffective stunning due to lack of maintenance and cleaning of the equipment, or wrong placement of electric tongs.

Stunning methods	Advantages	Disadvantages
Electrical stunning		Necessitates a short stun to stick interval (the time between stunning and sticking), which some slaughterhouses cannot accomplish unless the pigs are stuck on the floor.
		High risk of PSE meat, bruising, blood spots and bone fractures.
		Slaughter capacity is limited (maximum 600 pigs/hour per restrainer).
		More contact between the slaughterhouse staff and the pigs can stress workers and increase risk of injuries due to contact with the stunning equipment.
CO_2 stunning in groups	Pigs are handled in groups before and after stunning thus reducing stress for the pigs.	Gradual loss of consciousness.
	During pre-stunning handling and stunning, there is minimal to no human contact, thus reducing stress for the pigs.	Some pigs react to CO_2 with increased respiration, vocalisation and flight reactions.
	If the CO_2 concentration and exposure time is according to recommendations, there is a minimal risk of ineffective stunning.	A CO_2 system is approximately twice as expensive regarding the capital investment and operation costs compared to electrical stunning (e.g., MIDAS).
	Possibility of regulating the stun to stick interval by prolonging the duration of CO_2 exposure.	
	Low risk of PSE meat, bruising, blood spots and bone fractures.	
	Slaughter capacity can be high (up to 1200 pigs/hour).	

Background

The two most common stunning methods for pigs are electrical and CO_2 stunning. Both methods have advantages and disadvantages. CO_2 stunning is, by many, recognised as the best stunning method in terms of both animal welfare and meat quality. However, studies have shown that some pigs react to the gas in the seconds before loss of consciousness, and therefore the method has been criticised on the grounds of animal welfare. European Food Safety Authority (EFSA) has stated that CO_2 stunning should be phased out, and Eurogroup for Animals is calling for a ban on the use of CO_2 for stunning by 2025.

Researchers and companies are currently working towards developing new stunning methods. Alternative gasses in the form of argon and nitrogen, low atmospheric pressure stunning (LAPS) and nitrogen foam are examples thereof. Presently, there are no viable alternatives to CO_2 stunning in groups that provide better animal welfare and meat quality overall. Therefore, it is beneficial to examine existing stunning methods, describing strengths and weaknesses for future improvement of both existing and new stunning methods.

Objective

To investigate electrical and CO_2 stunning in groups, and the advantages and disadvantages of the methods regarding animal welfare and meat quality.

Effective stunning

The EU legislation on the protection of animals at the time of killing (Council Regulation (EC) No 1099/2009) is based on the premise that vertebrate animals are sentient beings and therefore have the capacity to experience pain and negative emotions such as stress (Terlouw et al., 2016). Furthermore, it is considered that slaughtering without stunning is associated with pain and distress (Council Regulation (EC) No 1099/2009). Therefore, an effective stunning can be defined as a stunning that induces unconsciousness and insensitivity in animals and furthermore ensures that unconsciousness is prolonged until death by exsanguination. This definition is used throughout this review.

The concept of consciousness consists of two factors: 1) being awake and 2) being aware of your surroundings and your own condition (Terlouw et al., 2016). (Un)consciousness can be determined by measuring brain activity using electroencephalogram (EEG). However, this is not possible in a slaughterhouse leaving the monitoring of the stunning effect to be performed by testing reflexes. Stimulation of reflexes involves the spine and brainstem. During unconsciousness, the brainstem will not be able to process information from stimuli, making it impossible for a reflex to be triggered. Testing of reflexes, typically the cornea reflex, can easily be done on CO_2 stunned pigs. However, it is difficult on electrically stunned pigs, as their bodies will be affected by involuntary movements because of the current. This led to a new EU requirement from December 2019 stating that the electrical stunning equipment must show and register the electrical parameters (amperage) related to stunning of each individual animal and give a warning should the stunning be ineffective (Council regulation (EC) No 1099/2009). Assessment of the electrical stunning can also be performed by observing the pigs' seizures. During application of the electrical tongs, their body should collapse, become rigid, and respiration should cease (tonic phase). After release of the tongs, their bodies should become flaccid, and involuntary movements caused by muscle contractions should commence (clonic phase).

Electrical stunning

Mechanism

During electrical stunning, a tong with electrodes is placed on the head of the animal, and current is delivered through the animal's brain. This results in an epileptic seizure (van der Wal, 1978) associated with a drop in pH in the blood, as well as the release of neurotransmitters leading to loss of consciousness (Cook et al., 1995). EEG measurements show that electrical stunning results in instant loss of consciousness (Llonch et al., 2013, Figure 1), and another study has shown that it is not associated with pain for the animal (Leach et al., 1980).

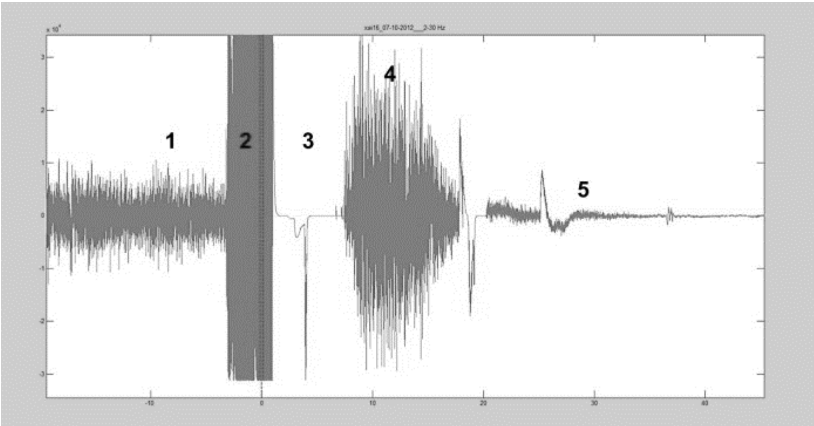

Figure 1. EEG measurements of a lamb during electrical stunning. 1) before stunning (normal EEG), 2) during application of current, 3) change in EEG as a result of the delivered current, 4) epileptic seizure, 5) resting potential (Llonch et al., 2013).

Pre-stunning handling

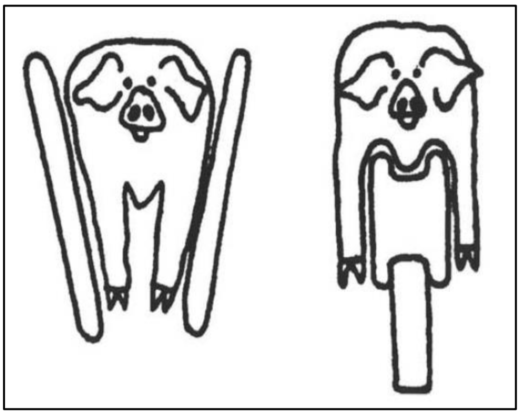

Figure 2. A V-restrainer on the left, and a conveyer restrainer on the right (Faucitano, 2010 – courtesy of P.D. Warris, University of Bristol, UK).

Electrical stunning can be performed in stunning pens where the operator approaches the individual pig thereby typically separating it from the other pigs. However, at slaughterhouses with a large output, groups of pigs are usually led down a raceway and into a restrainer such as a V-restrainer or a band restrainer (Figure 2). From a welfare point of view, stunning pigs in pens is preferred over a restrainer, but by using a restrainer and automatic application of electrodes, the slaughter capacity can be increased up to 10 times (from 30-60 to 150-600 pigs/hour; EFSA, 2004). Pigs can be reluctant to move forward in a raceway and go into the restrainer (Grandin, 2013), and it may require use of handling devices such as electric prods to make animals move forward, which can stress the pigs.

The electrical parameters

Currently, only alternating current is used to stun pigs. Yet, studies performed on chickens show that unconsciousness can also be induced by direct current although it requires a higher amperage.
It is the strength of the current, measured in amperes (A) that induces unconsciousness in pigs. As described by Ohm's Law, the current is determined by the voltage (V) and the resistance (Ω). In layman's terms, voltage can be thought of as a pressure that pushes the current through the animal, and resistance can be described as what the current encounters during its way through the head. The resistance is influenced by the thickness of the animals' skin, fat layer, skull, and hair. The EU legislation states that the current for stunning pigs must be at least 1.3 A (Council Regulation (EC) No 1099/2009) meaning that the voltage must be high enough in relation to the resistance to ensure that the induced current (the amount of current passing through the pig's head) reaches 1.3 A. Figure 3 illustrates how the voltage must be increased at greater resistance to achieve a current of 1.3 A. The recommendation of 1.3 A is based upon a study by Hoenderken (1978), however, other studies show that an amperage of as little as 0.4 A can also induce loss of consciousness (Anil, 1991; Végh et al., 2010). EFSA has stated that there is a need for revising most of the electrical parameters due to a lack of research.

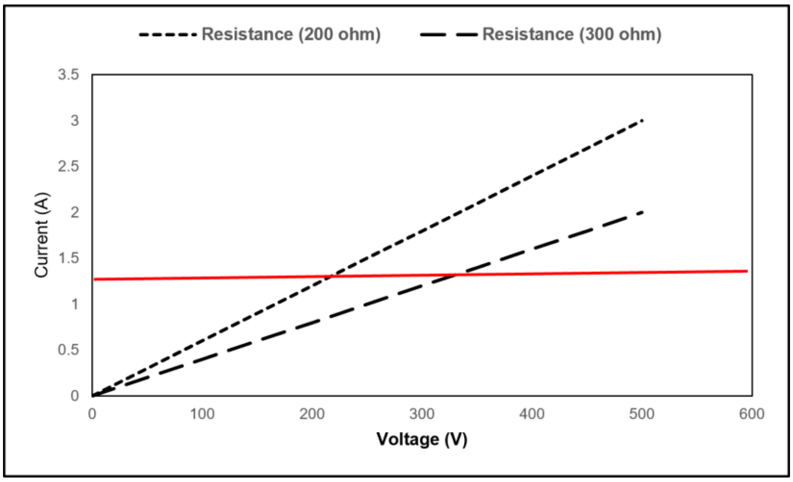

Figure 3. The product of resistance on voltage (V) and delivered current (A).

EFSA recommends an amperage of 200 V. However, studies show that a lower amperage, down to 90 V, can induce unconsciousness (Anil and McKinstry, 1992). Likewise, a high voltage (>200 V) is no guarantee for an effective stunning (Cook et al., 1995). From the research, it can be deduced that an effective stunning cannot be ensured by setting requirements for voltage alone, because it is affected by other factors such as frequency and resistance.

Frequency is the number of times one cycle of the waveform is repeated per sec., measured in hertz (Hz). The most optimal frequency for electrical stunning is 50-60 Hz (Croft, 1952). Studies has shown that a high frequency (1600 Hz) can also induce unconsciousness (Anil and McKinstry, 1992; Lambooij et al., 1996). A very high frequency (>1600 Hz) cannot render pigs unconscious and will most likely be painful (van der Wal, 1978). This is due to higher conductivity meaning that some of the current will be allocated to the pigs' skin rather than going through the pigs' heads resulting in a reduced induced current (Grandin, 1985; Sparrey and Wotton, 1997). Therefore, it is important to raise the voltage if the frequency is raised for instance for meat quality reasons.

Factors that affect resistance
Amperage, voltage, and frequency is usually pre-set by the producer of the equipment cf. EFSA's recommendations. If the correct equipment is used, but the stunning has been ineffective, it is usually due to increased resistance. This can be attributed to wrong placement of the electrical tongs, dirty or blunt electrodes or too short an exposure time (the time the pig is exposed to the current).

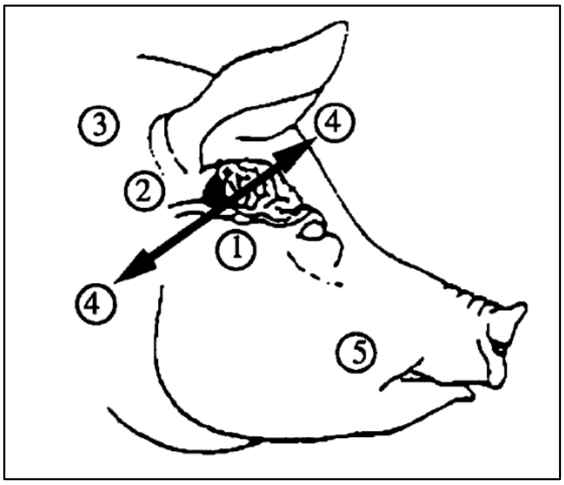

Figure 4. Placement of the tong electrodes (Anil and McKinstry, 1998).

The correct electrical tong position is important to ensure an effective stun as it influences the magnitude and path of the induced current. (Sparrey & Wotton (1997) and Anil and McKinstry (1998) tested 5 different placements and found that all placements except no. 5 (the jaw) resulted in an effective stunning (Figure 4). As stated by the EU legislation, the tongs should span the brain (Council Regulation (EC) No 1099/2009)). In practice, this means placing the tongs between the ears and eyes on both sides of the head. This means that placement no. 1 is the only acceptable placement.

Using dirty or blunt electrodes increases the resistance thereby reducing the induced current. Therefore, it is important to clean electrodes after each stun to ensure good contact with the pigs' head. Training of the personnel is important, as they must be able to recognise when the stunning has been ineffective, so that the pig can be stunned again, and the errors can be corrected.

The electrical stunning equipment cannot deliver a current strong enough to induce unconsciousness when applied for too short a time as there is a necessary breakdown of resistance entailed in the process, which requires time (Cook et al. 1995; Wotton & O'Callaghan, 2002). The longer the exposure time, the bigger the delivered current. A study shows that the exposure time should be for a minimum of 1 second to ensure an effective stunning at 1 A, 500 V and 50 Hz (Cook et al., 1995). One second is also the recommendations from EFSA at 1.3 A, minimum 200 V and 50 Hz. However, the longer the exposure time, the more breakdown of the resistance. It is recommended by professionals to have a longer exposure time. Most modern equipment is additionally secured with a safety device that does not terminate current application until after 3-4 seconds.

Sticking
Unconsciousness is maintained until the animal resumes regular respiration, usually 30-37 seconds after the start of applying the current (Anil, 1991; Vogel et al., 2011). Animals must remain unconscious until brain death. It takes an average of 18 seconds for a pig to lose brain function after exsanguination. Therefore, sticking is recommended within 10-15 seconds after stunning (Wotton and Gregory, 1986; Anil and McKinstry, 1992; EFSA, 2004). Some slaughterhouses may find this difficult to achieve, for instance due to a slow heist. This issue can be resolved by re-application of current to the heart to

induce cardiac arrest, which can be performed in two ways. Head-only stunning followed by applying current to the body (e.g., chest, side), or a head-to-body current can be applied where two electrodes are placed on the animal's head (e.g., behind the ears, forehead) and a third on the body (e.g., back, side) with a current passing to the two sites simultaneously or sequentially (Grandin, 2013). These stun-to-kill methods are irreversible and will kill the animal, which is positive considering animal welfare as it eliminates the risk of animals regaining consciousness before brain death (Vogel et al., 2011). Stun to kill methods also result in greater work safety, as the carcass is more relaxed after a cardiac arrest making it easier to perform sticking. In the EU, only the first method is used.

CO_2 stunning in groups

Mechanism

CO_2 causes a decrease in pH in both the blood and the cerebrospinal fluid. This causes the brain's glucose metabolism to cease, causing a lack of energy being delivered to the brain. Furthermore, it generates a disturbance in the neural transmission in such a manner that the brain becomes unable to maintain its normal function (van Nimmen et al., 1984; Martoft et al., 2002; Rosival, 2011). CO_2 causes a gradual loss of consciousness, which is a disadvantage from an animal welfare point of view, as some pigs initially react to the gas (Dodman, 1977; Dalmau et al., 2010; Smith et al., 2018). Studies have shown that CO_2 does not cause direct activation of nociceptors (nerve cells that register pain) in the mucous membranes of the respiratory tract (Strøbech, 2008). Therefore, it is assumed that it is the acidification in the mucous membranes of the respiratory tract that activates both nociceptors and receptors involved in processing pain (Strøbech, 2008). The body will also respond to an increase in CO_2 by increasing the respiratory rate to get rid of the excess CO_2 in the blood. However, as CO_2 increases, respiration will become more and more difficult, which is accompanied by a feeling of shortness of breath incomparable to normal accumulation of CO_2 in the blood, as experienced e.g., during body activity (Stark et al., 1981).

Pre-stunning handling

CO_2 stunning in groups eliminates the need for restraining pigs and makes it possible to stun them in groups. This a profound benefit to animal welfare. Pigs are easier to handle in groups, because they naturally follow each other. This reduces stress during the driving of pigs to the stunner (Correa et al., 2010) and reduces the need for boards, paddles, and electric prods. Furthermore, plants with CO_2 stunning can employ a semi-automatic driving system leading up to the stunner with push gates that gently drive the pigs forward. These automatic systems reduce the contact between personnel and pigs, which also lowers the stress for the pigs. The latest developed CO_2 systems (Backloader, Marel) can facilitate a slaughter capacity of 100 to 1090 pigs/hour, which is more pigs than even the largest electrical stunning system can handle.

Reaction to CO_2

There is a consensus among researchers that CO_2 causes a reaction in some pigs during induction of the gas. However, the degree of reaction and thus aversion to CO_2 is difficult to determine. One study showed that even after 24 hours of fasting, 88% of the pigs were reluctant to go into a room pre-filled with 90% CO_2 even though it contained apples (Raj and Gregory, 1995). Another study showed a similar strong response where pigs would rather go 72 hours without water than to be exposed to CO_2 (Cantieni, 1976). In contrast, one study showed that pigs simply stood still when exposed to CO_2 (Troeger and Woltersdorf, 1991), and another study concluded that the shock from an electric prodder elicited a greater response from pigs than CO_2 (Jongman et al., 2000). The difference in results indicates that pigs react differently to CO_2, with some showing strong responses and others only showing subdued responses. The reaction to CO_2 is possibly linked to the breed and genetic background of the pig (Grandin, 2013) as research suggests that pigs carrying the halothane gene react more strongly to CO_2 (Velarde et al., 2007). The reaction to CO_2 can also be connected to the handling of the pigs prior to stunning, with stressed pigs reacting more strongly (Terlouw et al., 2008; Jongman et al., 2021). Reaction to CO_2 depends on the concentration, which must exceed 30% to elicit a reaction from pigs (Raj and Gregory, 1996). In addition, the higher the concentration, the greater the percentage of pigs reacting and the greater the degree of reaction (Raj and Gregory, 1996; Velarde et al., 2007; Verhoeven, 2016). The EU requires a concentration of minimum 80% in the first position, and EFSA recommends a minimum of 90% in the bottom position (EFSA, 2004) on the grounds that the time until loss of consciousness reduces with greater concentration. Stress is also linked to being confined and immersed in the stunning system (Dalmau et al., 2010). There is no consensus among studies on when loss of consciousness occurs at high CO_2 concentrations (>80%). Some studies indicate that loss of consciousness occurs around 12-17 seconds after exposure, while others indicate it occurs 20-22 seconds after exposure. Finally, more recent studies indicate 33-60 seconds after exposure (Table 2). The difference in results can likely be explained by the method by which the pigs have been exposed to CO_2. A direct exposure to a high concentration of CO_2 will cause unconsciousness to occur earlier compared to a gradual exposure (Verhoeven, 2016). In a commercial CO_2 stunning system, pigs are immersed in CO_2 in a pit. This results in a lower concentration of CO_2 at the entrance than at the bottom, and exposure will thus be gradual. However, even in studies where the exposure method has been the same, there will likely be a difference in time to exposure to maximum concentration. As an example, it took 23 seconds before pigs in Rodriguez et al. (2008) were exposed to CO_2, but only 15 seconds in Velarde et al. (2007). Furthermore, the studies mentioned have measured consciousness and lack thereof differently via e.g., EEG and observation of the animals (loss of balance). Both methods have uncertainties. Even interpretation of EEG measurements, which is believed to be the most objective method for measuring consciousness (EFSA, 2004), can achieve different conclusions across studies; as previously mentioned, loss of consciousness is a gradual process. Some studies have stimulated pigs during exposure to CO_2 e.g., using sound. This method is defined as auditory evoked potentials (AEP). With the help of EEG measurements, the pig's reaction to stimuli can be related to its degree of awareness. This method is commonly used on humans and may be able to assess the level of consciousness under stunning with more precision, but the method has the same disadvantages as EEG. Conclusively, it is difficult to define exactly when loss of consciousness occurs during CO_2 stunning as it depends on several factors related to both the environment and the measure method.

Table 2. Effect of high concentration of CO_2 (85-90%) on time until loss of consciousness.

Reference	CO_2 concentration (%)	Time until loss of consciousness (sec.)	Method of exposure	Method of measurement
Forslid (1992)	95	12	Pigs in a cage immersed in a pit with CO_2	EEG
Raj et al. (1997)	80-90	20-21	Pig in a sling inside a box with CO_2	EEG
Raj (1999)	80-90	17	Pigs in a cage immersed in a pit with CO_2	Loss of balance
Martoft et al. (2001)	90	12-14	Pig in a sling inside a box with CO_2	EEG, Auditory evoked potential (AEP)
Velarde et al. (2007)	90	22	Pig immersed in a commercial dip-lift system (Marel A/S)	Loss of balance
Rodriguez et al. (2008)	90	60	Pig in a sling immersed in a commercial dip-lift system (Marel A/S)	EEG, Auditory evoked potential (AEP)
Llonch et al. (2013)	95	37	Pig immersed in a commercial dip-lift system (Marel A/S)	EEG
Verhoeven (2016)	95	26-33	Pigs (a pair) immersed in a commercial dip-lift system (Marel A/S)	Loss of balance, EEG

Muscle excitation, also defined as muscle contractions, occurs in some pigs during CO_2 stunning (50-100%; Forslid, 1992; Dalmau et al., 2010; Verhoeven, 2016). However, there is disagreement among researchers whether it happens before or after loss of consciousness. EFSA has described it as the brain not being able to regulate the connection between the reticular formation and the cerebral cortex, the areas of the brain that process wakefulness and sensory information, but it is not known why this occurs, and when. Some studies indicate that muscle excitation occurs immediately during or after unconsciousness (Forslid, 1992; Martoft et al., 2002). Whereas other studies indicate that it may occur before loss of consciousness (Velarde et al., 2007; Rodriguez et al., 2008; Dalmau et al., 2010; Verhoeven, 2016) possibly associated with pain (Dalmau et al., 2010). Grandin (2013) suggests that it may also depend on breed, with excitation occurring after loss of consciousness in Yorkshire, but before in other breeds.

Dwell time and sticking

Compared to electrical stunning, CO_2 stunning can prolong the time pigs are unconscious after stunning. In this way, the stun to stick interval can be regulated, which reduces the risk of pigs regaining consciousness before death by exsanguination. However, a longer stun to stick interval is also necessary as several pigs are stunned at the same time. Maximum stun to stick interval depends on CO_2

concentration and dwell time (i.e., the total time pigs are in the CO_2 facility). According to EFSA, the corneal reflex is allowed briefly in <5% of the animals, provided that other reflexes are absent. Nowak et al. (2007) found that in cases with 90% CO_2 at the bottom position and with an exposure time of 100 seconds and a maximum stun to stick interval of 40-50 seconds, 5.9% of the pigs showed a corneal reflex, suggesting a stun to stick interval of maximum 40 seconds at a dwell time of 100 seconds. Based on Holst (2001), EFSA has made recommendations for dwell time, assuming a CO_2 concentration of minimum 70-80% in the first position and 90% in the bottom position, including a minimum dwell time of 120 seconds and maximum stun to stick interval of 30 seconds (Table 3). The stun to stick interval can be extended by 15 seconds following an increase in dwell time of 10 seconds (EFSA, 2004). However, Marel recommends a minimum dwell time of 120 seconds. The stun to stick interval also depends on the stunning facility and group size. Therefore, it is important that the individual slaughterhouse examines reflexes after stunning/sticking and regulates the stun to stick interval accordingly. Finally, CO_2 stunning has the advantage of higher work safety associated with sticking as the carcass is completely relaxed after CO_2 stunning.

Table 3. Stun to stick interval depending on dwell time (i.e., total time where pigs are in the CO_2 facility) provided a minimum concentration of 70-80% CO_2 in the first position and 90% CO_2 in the bottom position (EFSA, 2004).

Dwell time	Stun to stick interval
100	30
110	45
120	50
130	65
140	80

Meat quality

Electrical and CO_2 stunning elicit muscle contractions and release of catecholamines, inducing muscle glycolysis; the process of breaking down glucose to lactate. The level of glucose in the muscles mainly determines the pH development and ultimately the pH value in the meat. Electrical stunning results in more severe muscle contractions than CO_2 stunning because as current is applied, all muscles are stimulated simultaneously and will contract as part of the seizure, which causes an increase in intramuscular pressure and blood pressure in the vessels (Becerill-Herrera et al., 2009). For this reason, studies show that electrical stunning results in more muscle haemorrhaging compared to CO_2 (Lambooij, 1994; Velarde et al., 2000). In addition, electrical stunning can result in bone fractures which are only rarely seen in CO_2 stunned pigs (Larsen, 1983; Channon et al., 2003; Marcon et al., 2019). Electrical stunning using high frequencies (>60 Hz) have shown to cause less damage on the spine (Marcon et al., 2019) and a lower voltage (29 V) has shown to cause less muscle haemorrhaging (Lambooij, 1994). This is due to a lower induced current leading to a possible conflict between animal welfare and meat quality. An ineffective first stun, which necessitate a second stunning, results in more muscle contractions (van der Wal, 1978). This emphasises that for both animal welfare and meat

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quality, it is important to have an effective stunning the first time. Electrical stunning with cardiac arrest can have a positive influence on the meat quality, as the muscle contractions will cease earlier, and the carcass will be more relaxed making sticking easier (Grandin, 1985). A study shows that electrical stunning with cardiac arrest generally does not have a negative influence on pH, drip loss or colour in the meat, compared to electrical stunning, where the current is only applied to the head (Vogel et al., 2011). It is recommended to first apply the electrical tongs on the head, and then apply the tongs on the side/chest, rather than using electrical tongs with three electrodes placed on the neck/back, as the neck is not an optimal placement of the tong electrodes in terms of animal welfare. This is because 1) The current does not reach the brain along the shortest path, leading to higher voltage needed to reach minimum current of >1.3 A (Vogel et al., 2011) and 2) It results in fewer muscle contractions and better meat quality (Wotton et al., 1992).
As pigs are CO_2 stunned in groups, the pre-stunning handling is often gentler compared to electrical stunning. This promotes a slow pH development post-mortem (Warris et al., 1994; Støier et al., 2001) and concomitantly lowers the risk of PSE-meat (Larsen, 1983; Velarde et al., 2000; Channon et al., 2003). Possibly due to stress associated with the gas exposure, studies show that a CO_2 concentration of 60-80% causes a lower pH below the optimal level in meat (<5.6) compared to a CO_2 concentration of 80-90%, which can negatively affect e.g., drip loss and meat colour (Troeger and Woltersdorf, 1991; Nowak et al., 2007).

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