Poultry Science

Are spiritual, ethical, and eating qualities of poultry meat influenced by current and frequency during electrical water bath stunning?

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ABSTRACT With the continuous rise of Muslim and Jewish populations and their increasing preference for ritually slaughtered poultry meat, the industry is forced to redefine its existing product-centric quality standard toward a new consumer-centric dimension of quality. The new dimension is mainly attributed to ensuring animal welfare and ethical treatment (ethical quality), spiritual quality (such as halal status, cleanliness), and eating quality standards set by religion. To meet consumer quality requirements while maintaining high production performance, the industry has incorporated newer technologies that are compatible with religious regulations such as stunning methods like electrical water bath stunning. However, the introduction of new techniques such as electrical water bath stunning has been met with mixed reactions. Some religious scholars have banned the use of any stunning methods in religious slaughter, as halal status is believed to be compromised in cases where birds have been stunned to death before slaughter. Nevertheless, some studies have shown the positive side of the electrical water bath stunning procedure in terms of preserving eating, ethical, and spiritual quality. Therefore, the present study aims to critically analyze the application of various aspects of electrical water bath stunning such as current intensity and frequency on various quality attributes, namely, ethical, spiritual, and eating quality of poultry meat.

Key words: electrical stunning, halal slaughter, ethical quality, spiritual quality

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INTRODUCTION

The poultry industry has experienced a significant increase in demand in recent years compared to other meat industries due to rapid turnover, cheaper prices, and high availability (Joo et al., 2013, Ismail and Joo, 2017), efficient feed conversion, absence of any social taboos (Naveena et al., 2013), all-in-all-out concept and good quality attributes of poultry meat (Kumar et al., 2022). Although the COVID-19 pandemic caused a major setback in total animal meat production in 2020, the poultry industry is still strong and has been able to absorb the decline in consumption compared to the other animal meat industry. It is also worth noting that the United States Department of Agriculture (USDA, 2017) has projected that after the pandemic subsides, total poultry meat production will increase by 2% over prepandemic levels due to fluctuations in consumer demand.

Meat quality, in general, has always been associated with eating quality traits such as tenderness, marbling, juiciness, and color, which have been used as an indicator of consumer acceptance and willingness to purchase. However, for some groups of consumers, such as Muslim and Jewish communities, eating qualities are not considered the sole criteria for acceptance, as meat is considered unworthy for consumption if it is not produced by slaughtering animals per the prescribed religious guidelines (halal/kosher). Consequently, a new set of meat quality standards have been proposed, which includes the so-called religious quality, aside from the common eating and ethical quality. Hence, the poultry industry must improvise and incorporate technologies to meet high production rates and meet all meat quality standards.

In this review, the association between the electrical water bath stunning procedure and meat quality (religious, ethical, eating) is reviewed in light of recent scientific developments (Figure 1).

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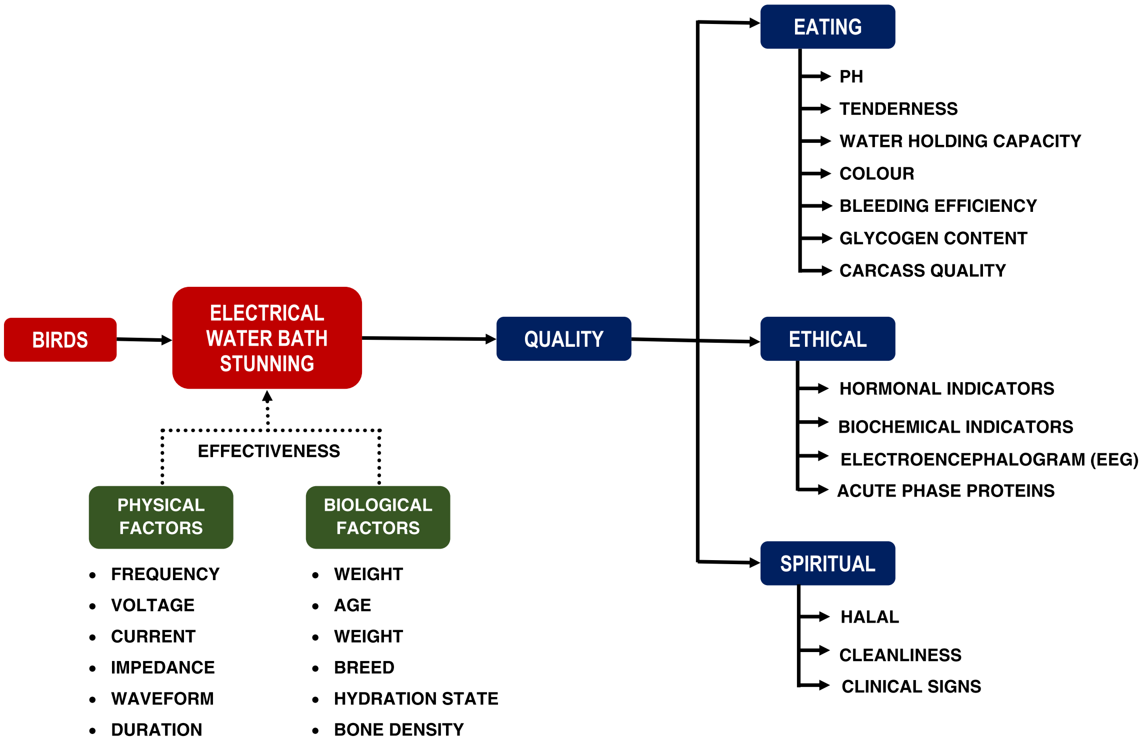

Figure 1. Spiritual, ethical, and eating qualities of poultry meat as determined by the efficacy of electrical water bath stunning.

NEW DIMENSIONS OF QUALITY

Quality optimization has been regarded as one of the main focuses in most scientific studies, especially in food-related research. Traditionally, quality-based research studies focused on improving eating quality (Liu et al., 2011; Oliveira et al., 2014; Park et al., 2016; Hayat et al., 2021). However, a new emerging concept of quality has caused a revolution in the overall understanding of quality from a consumer's point of view.

In addition to eating quality, spiritual and ethical quality have been included as one component of overall food quality, and their importance toward consumer acceptance has been widely acknowledged. The foundation and interrelation between these 3 quality components have been thoroughly discussed by Farouk et al. (2004) , in which the authors have shown the importance of each component toward consumer acceptance (Figure 2).

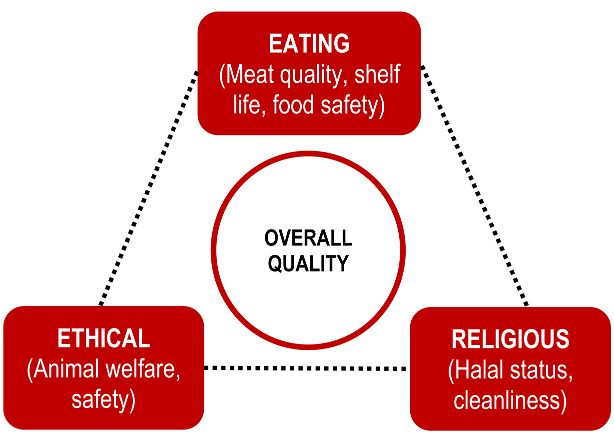

Figure 2. New definition of meat quality.

Spiritual Quality

Spiritual quality has become the main factor or the foundation for food-based product acceptance for some major religious communities worldwide. For them, animals that have undergone a good processing procedure and hygiene practices would still be considered not spiritually fit for consumption if it is not processed based on their religious guidelines (Farouk et al., 2004). Spiritual quality will be achieved if the meat is processed according to the religious guidelines and requirements, which may occur before, during, or after the meat is processed. Generally, there are a lot of slaughter management practices performed by various religions and cultures all around the world. However, the most well-known processing methods are halal and kosher, by Muslims and Jewish communities, respectively (Farouk et al., 2014). The word halal indicates an action or operation acceptable in Shariah Law. It is mostly used for food products that meet spiritual quality and are suitable to be consumed by Muslims (Che Man and Sazili, 2010).

With an increase in Muslim and Jewish populations worldwide, the demand for halal and kosher meat has become increasingly high, thus pushing the poultry industry to improvise and incorporate these religious requirements during meat production. Generally, halal and kosher meat production revolves around the method of killing an animal, which is neck cutting. The neck-cutting procedure must be done by a trained individual from their respective religions, and the ventral neck cut must be done by severing the trachea, esophagus, both carotid arteries, and jugular veins. During the process of neck cutting, the slaughterer must ensure that no incidence of head decapitation has occurred (Che Man and Sazili, 2010; Farouk, 2013). Animal death must only be caused by neck-cutting procedures, not by other means.

Ethical Quality

Ethical quality is another interesting component of food quality that has recently come into focus, mostly associated with animal welfare and the overall management of an animal. The rise in consumer demand for high-quality, safe, and ethically produced food may stem from their awareness of a healthy lifestyle, nutritious diet, and in some cases, the prevalence of cases and reports of animal abuse or mistreatment during processing. An animal that was supposed to be slaughtered for food production needs to be processed so that the animal's welfare is well-taken care of. Farm Animal Welfare Council (FAWC) (1992) stated that good animal welfare is achieved when animals are provided with 5 types of freedoms which are 1) freedom from hunger and thirst, 2) freedom from discomfort, 3) freedom from pain, injury, and diseases, 4) freedom to express normal behavior, and lastly 5) freedom from fear and distress.

Although various methods and technologies have been implemented to improve animal welfare management in farms and processing plants, some animal welfare aspects still need attention. The "freedoms" stated above are sometimes intertwined with each other, thus causing good animal welfare management during meat production to be quite tricky to achieve. For instance, birds reared for food production may be kept in a closed cage to have their freedom from hunger and thirst; however, at the same time, they are restricted from their freedom to express normal behavior.

Generally, animals processed for halal and kosher meat production cannot undergo a stunning procedure. Some Muslim countries have disallowed the usage of stunning because of the fear that the stunning method might lead to suspicious halal management and status (Nakyinsige et al., 2013; Fuseini et al., 2016). Halal meat must only be obtained from animals that had died due to neck-cutting procedures. However, some cases of animal death due to improper or unsuitable stunning procedures might compromise the halal status (Sirri et al., 2017).

The welfare issues regarding the stunning procedure that is not permissible in halal and kosher meat production remain controversial (Grandin, 2017). Previous researchers reported several welfare issues related to stunning procedures. For instance, Zulkifli et al. (2019) reported that animals slaughtered using the halal slaughtering method might suffer from pain because they did not lose their insensibility compared to animals slaughtered after the stunning procedure. Stunning will induce insensibility in the animal if done efficiently; hence, it eases the neck-cutting process, which benefits both the animal and the slaughterman. However, it is worth noting that the stunning system needs to be well maintained, and the procedure must be done appropriately to avoid any incidence of overstunned or understunned birds. Besides that, several other welfare concerns need to be addressed during an electrical water bath stunning procedure, such as unnecessary pain due to shackling and the inverted position that the birds need to be placed so that the system will work efficiently (Ismail et al., 2019; Zulkifli et al., 2019).

Eating Quality

Eating quality relates to consumer acceptance of meat characteristics such as color, texture, flavor, and juiciness, which are markedly affected by meat quality. From a consumer point of view, meat that satisfies all the consumer's requirements is considered high in quality. However, the perception of good eating quality may differ from one individual to another due to differences in demographic and psychographic backgrounds.

Consumer acceptance and eating quality are highly affected by meat quality (Adzitey, 2011). Meat quality is a trait attained from the combination of biological (breed, health status, diseases, glycogen concentration) and environmental factors (stunning method, slaughtering method, processing temperature, storage duration, storage temperature) (Ab Aziz et al., 2020). All the listed factors may contribute, individually or in combination, to the final product meat quality. For instance, Chambers et al. (2001) highlighted that if an animal is placed under a stressful condition before and during slaughter, the glycogen stored in the animal muscle is consumed, resulting in reduced lactic acid development in the muscle. As meat pH increase, water-holding capacity (**WHC**) is affected, thus, resulting in the production of dark, firm, and dry (**DFD**) meat. DFD meat is unfavorable among consumers due to the unappealing color presentation and lack of juiciness.

The wooden breast (**WB**) is an emerging quality defect in poultry associated with fibrosis/ myopathy, increased deposition of collagen, and accumulation of connective tissues along with the presence of small hemorrhages or viscous fluid and white stripping (Sihvo et al., 2018; Soglia et al., 2016). Histologically, WB fillets show polyphasic myodegeneration exhibiting degenerative and atrophic fibers, fibrosis, lipidosis, cell infiltration, vacuolar degeneration, and occasional regeneration (Sihvo et al., 2018). The WB fillets are characterized by palatable toughness, pale color areas, and caudal protuberance (Sihvo et al., 2014). These fillets have lower WHC and cooking yield and are mostly condemned by the industry (Geronimo et al., 2022).

Achieving an optimum eating quality for meat is the highest priority among industrial players and researchers. Regardless of the methods used in meat production, improving appearance, texture, juiciness, tenderness, odor, and flavor are the most important meat quality parameters that must be addressed. These factors affect the meat quality and consumers' decision to purchase the meat product (Farouk et al., 2014; Mir et al., 2017). WHC, for instance, had been the major subject of interest for researchers because an increase in water content within the muscle would cause tenderness, juiciness, texture, and appearance of the meat to be improved and lead to better production of meat and uplift its economic value (Warner, 2017).

POULTRY PROCESSING

Due to the fluctuation in demands for poultry meat, a lot of research and studies have been conducted to improve the production and quality of the end product (Joseph et al., 2013; Petracci et al., 2015; Bostami et al., 2021; Hayat et al., 2021). These advancements have caused a significant increase in meat production and improvement in final meat quality. However, at the same time, the concern in fulfilling the demand for poultry meat that meets all spiritual or religious quality requirements has led industrial players and researchers to incorporate the religious practices of each religion into the existing processing technology. A poultry processing plant is at the center of a farm-to-table food chain. Thus, everything that revolves around maintaining quality, both spiritual and meat quality, must be addressed before it reaches the consumer.

Halal meat is produced based on a series of processes and procedures stated in the Shariah law. The traditional way of slaughtering an animal according to the religious condition is considered slow and does not abide by animal welfare requirements. However, the fluctuation in demand for halal meat worldwide has triggered much improvement in the whole halal processing. Incorporating modern technologies in the traditional halal slaughtering procedure, without violating any religious restriction, has caused major improvement in poultry meat production. The production volume and the quality of meat produced were much better, thus satisfying the demands for halal poultry meat products worldwide.

However, some communities who oppose incorporating technologies in halal poultry meat processing believe there is a fear of halal status being compromised due to the lack of monitoring and inefficient machine functions. They believe animals should be slaughtered according to the prophetic method (Farouk et al., 2014). Some of the issues related to the halal stunning procedure are as follows: the probability of the animal dying before slaughter, the difficulty in identifying the dead animal and removing them from the shackle conveyor system, the effect on the blood volume and bleeding efficiency, carcass downgrading, and decrease in meat production (Fuseini et al., 2016). There is also a probability of birds suffering from more pain due to an incidence of prestun shock (Khalid et al., 2015). Daly (2005) reported that poor carcass quality observed in an electrical stunning was associated with the rapid decline in pH due to animals' struggle during stunning.

Other halal meat processing issues include fraud or deceptive halal status, foreign workers (questionable practices), and integrity. The prevalence of a newly found syndicate, in which meat with questionable halal status was imported from countries, causes numerous questions/doubts about whether halal meat is fit to be consumed by Muslims.

THE ELECTRICAL WATER BATH STUNNING

The improvement in poultry processing technologies has become apparent, especially due to fluctuating consumer demand. The urge to increase poultry meat production while at the same time maintaining both superior meat quality and better animal welfare management had caused much time and financial investment to be endowed by the industry.

Nowadays, the electrical water bath stunning system is more commonly used in commercial poultry processing plants. Farouk (2013) reported that most Muslim countries and communities had accepted the usage of stunning in halal poultry meat production because the overall stunning procedure would not lead to death before slaughtering.

General Principle of Electrical Stunning

Stunning systems were developed to induce insensibility to pain in animals until death. Currently, the electrical water bath stunning procedure is the only halal-compliant method to render a bird unconscious (Farouk, 2013; Joseph et al., 2013). The stunning procedure starts when the birds are removed from crates and then shackled on a moving conveyer before entering the water bath (Nakyinsige et al., 2013). Conscious birds that were hung on a shackle line will then come in contact with the electrified water bath, in which the current will flow from the head (disrupting brain function) to the entire body toward the shackle (Che Man and Sazili, 2010; Joseph et al., 2013; Berg and Raj, 2015; Shahdan et al., 2016). Unconsciousness is obtained from a generalized epileptiform seizure in the brain (Sabow et al., 2017).

The basic requirements of an electrical water bath stunning system must be fulfilled to ensure that the stunning procedure is carried out efficiently, as mentioned in Figure 3 (Raj and Tserveni-Gousi, 2000).

FACTORS AFFECTING THE EFFICACY OF ELECTRICAL STUNNING

The efficacy of an electrical water bath stunning system can be affected by various factors. These factors can be grouped into 2 major categories: biological and physical. These factors may, individually or in combination, influence the efficacy of electrical water baths stunning.

Physical factors include electrical voltage, current, frequency, waveform [alternate current (**AC**) or direct current (**DC**)], and duration of stunning (EFSA, 2004; Raj, 2006; Hindle et al., 2010; Salwani et al., 2015;

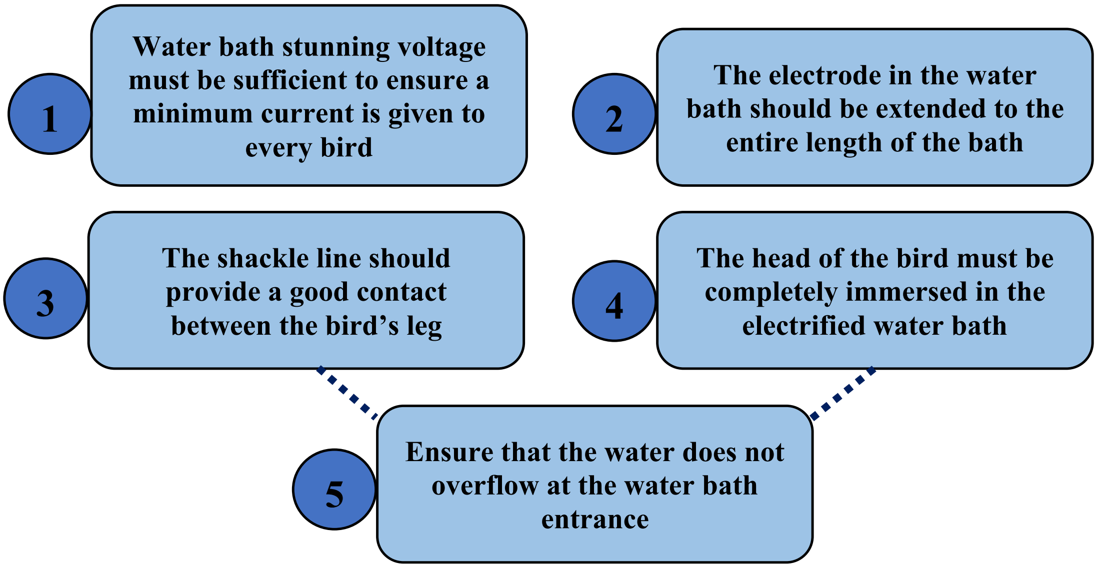

Figure 3. Basic requirements for electric water bath stunning system.

Sabow et al., 2017). For instance, electrical current is the flow of electrical charge that moves through an animal's body and disrupts normal brain function, thus resulting in unconsciousness and insensibility. However, the current/ current flow rate that can go through an animal body depends on the amount of electrical voltage supplied and the resistance (as per Ohm's law). Resistance, on the other hand, is mostly related to the biological properties of the animal itself, which will be further discussed in the following chapter. Biological factors include birds' size, breed, sex, and weight (Berry et al., 2016; Ismail et al., 2019).

Physical Factors

As previously mentioned, the efficacy of electrical stunning can be influenced by physical factors such as current, frequency, waveform (AC or DC), voltage, and duration of electrical exposure in birds (Raj, 2006; Ali et al., 2007; Hindle et al., 2010; Salwani et al., 2015; Sabow et al., 2017), which are categorized as physical factors. These factors can be adjusted to cause an animal to be stunned or stunned-killed after the procedure. Previous studies have shown that high-frequency stunning had more beneficial outcomes regarding religious/spiritual, ethical, and meat quality than low-frequency stunning. The main requirement is to use high-frequency electrical stunning procedures per the spiritual quality, as the animal does not die due to cardiac arrest during the stunning procedure (Farouk et al., 2014; Wotton et al., 2014). It is also unlikely that the animals will suffer severe muscle contraction, muscle hemorrhages, and broken bones when subjected to stunning high-frequency procedures (McNeal et al., 2003; Simons et al., 2006). Moreover, it has been reported that high-frequency stunning may increase bleeding efficiency and meat quality while minimizing carcass damage (Gregory, 2005; Simons et al., 2006). Sabow et al. (2017) stated that the stunning effect of a high-frequency procedure is reversible, while low frequency may tend to induce cardiac arrest. However, other factors, such as the amplitude and magnitude of current or voltage, still need to be considered.

Voltage is the electrical force that pushes the flow of current throughout the body and brain of an animal. Studies have shown that low voltage can contribute to poor bleeding and higher carcass defects (Gregory, 2005; Sabow et al., 2017). Ensuring an adequate voltage supply is crucial for the animals to be properly stunned. However, some studies reported that high voltage could also cause heart fibrillation, leading to ineffective bleeding, hemorrhaging, and even death before exsanguination, which goes against the spiritual/ religious quality/ halal requirements (Grandin, 2006; Hindle et al., 2010).

During electrical water bath stunning, the duration of exposure to the electrified water bath is also an important factor and needs to be closely monitored. Birds insufficiently exposed to the electrified water bath may gain consciousness right before neck cutting. On the other hand, birds that were exposed for too long might be subjected to ecchymosis (Devine et al., 1993; Gilbert et al., 1984; Fernandez et al., 2003; Farouk et al., 2014), cardiac arrest, and death which compromise the halal status/religious quality.

Biological Factors

Aside from physical factors, biological factors such as health condition, animal size, weight, sex, breed, age, feather distribution, skin and leg scale thickness, breast muscle and fat composition, total water percentage in the body, and the density and thickness of the skull and tarsometatarsal bone play an important role in determining the efficacy of electrical stunning (HSA, 2015). These factors are associated with how much resistance the birds will give to the current flow. Electrical current needs to supersede the resistance to achieve a stunning effect.

Table 1. Electrical resistances of poultry.

Bird type	Sex	Average resistance (Ω)	Range of resistance (Ω)	Live weight (kg)/average weight range (kg)
Broiler	Male	900+	800−3900	2.5/(1.7−3.5)
	Female	1200+		
Egg-laying (layer)	Female	2500−2900	800−7000	1.9/(1.3−2.4)
Turkey	Male	1200−1600	Up to 5700	8−25
	Female	2100−2300		5−10
Guinea Fowl	n/a	2900	n/a	1.2−2.3
Duck	n/a	1600−1800	900−2800	2−3.8
Goose	n/a	1900	4100	4.3−6.7

Source: Electrical Water bath Stunning of Poultry, Humane Slaughter Association (HSA), Hertfordshire, United Kingdom (https://www.hsa.org.uk/downloads/publications/hsaonlineguidewaterbathpoultryapril2016.pdf). Accessed 10 September 2021.

It is worth noting that even individual birds of the same type (e.g., broiler) have different resistance to the electrical current due to variations in the distribution of tissues, muscle, and fat throughout their body. The distribution of tissues, muscle, and fat is important because they have different electrical conductivity. Aside from that, variation between different strains, breeds, and species had a bigger impact on resistance to electrical current (Table 1).

Additionally, weak birds suffering from diseases or energy deprivation from prolonged crate-holding periods are unlikely to survive the stunning procedures. The different breeds might also cause a different impact on the efficacy of stunning, in which larger breeds, such as breeders and layers, might have higher resistance toward the electrical voltage and frequency. As mentioned previously, for halal meat production, the death of an animal can only be caused by neck cutting and not by other means. Thus, birds that did not survive the stunning procedure are considered unfit for Muslim consumption. A more thorough study needs to be conducted to investigate the effect of biological factors on the efficacy of the head-only electrical water bath stunning procedure.

TYPES OF ELECTRICAL WATER BATH STUNNING

Generally, an electrical water bath stunning system can be divided into 2 groups. The head-only electrical water bath stunning systems, incorporated in a halal processing plant, and the head-to-body electrical water bath stunning system were massively used in Western countries.

Head-Only Electrical Water Bath Stunning System

As mentioned, the head-only electrical water bath stunning system has been chosen to be incorporated into a halal processing plant. The main reason for the decision was the irreversibility of the stunning effect on birds. The stunning effect is achieved by passing a current via the brain from one side of the head to the other (Sabow et al., 2017). Suppose a sufficient amount of current is supplied to the brain. In that case, an overstimulation state in the brain will occur, activating all neurons at once, similar to grand mal epileptic seizure (Sabow et al., 2017).

In an electrical water bath stunning system, the “live” electrode is placed in the water bath while the other, the “earth” electrode, is situated above the water bath so it is in contact with the shackles (Raj, 2006; Lines et al., 2011a; Gibson et al., 2016). The birds will be shackled in an upside-down position, allowing the current to flow from the head to the feet through the body, resulting in brain-stimulated generalized epilepsy (Lines et al., 2011a). Lines et al. (2011a) reported that the prevalence of epilepsy in birds stunned using an electrical water bath stunning procedure produces a highly synchronized 8 to 15 Hz activity when observed via electroencephalogram (**EEG**), an indicator of consciousness and sensibility.

Head-to-Body Electrical Water Bath Stunning System

Head-to-body electrical water bath stunning systems are currently used in processing plants that do not comply with halal meat production requirements. The method subjected the animals to 2 types of induction, viz., an epileptic state in the brain and cardiac arrest at the heart simultaneously. The stunning system is intended to ensure that the animal does not recover after stunning, thus contradicting halal compliance (Sabow et al., 2017). However, the method has been deemed to be better regarding animal welfare due to its irreversibility caused by halting heart function (Schatzmann and Jäggin-Schmucker, 2000; World Organisation for Animal Health (OIE), 2019). As a result, the risk of carcass downgrading is reduced, and the safety of workers is better assured (Agbeniga and Webb, 2012).

Combinations of Electrical Inputs

Many trials have demonstrated the potential of product quality degradation, such as muscle contraction, cardiac arrest, breast muscle hemorrhages, and broken bones are more common at low frequencies (50−60 Hz) and current (120 mA) combinations (Hindle et al., 2010). To reduce the issues associated with low-frequency stunning in poultry, high-frequency electrical stunning is commonly used in the poultry industry (Prinz, 2009; Fernández-López et al., 2010). However, the drawback is that a high-frequency stunning system requires greater current intensities to be effective (EFSA, 2004; Raj, 2006; Prinz et al., 2010a; Girasole et al., 2015).

An effective electrical frequency and voltage combination during stunning will minimize stress levels without adversely affecting broiler chickens' recovery and bleeding efficiency. For instance, low-voltage electrical stunning has been reported to cause poor bleeding and high carcass defects (Gregory, 2005). On the contrary, high voltage can also cause heart fibrillation, leading to ineffective bleeding, hemorrhaging, and even death before exsanguination (Hindle et al., 2010). HSA (2015) and Lambooij and Hindle (2018) mentioned that when higher currents and frequencies are applied during stunning, birds will immediately lose consciousness; however, it will affect the carcass quality due to muscle hemorrhaging.

Various aspects of the electrical water bath stunning of poultry are presented in Table 2.

Electrical Inputs and Stunning

The level of insensibility varies based on the combination of the electrical inputs in poultry. Inadequately stunned (under stunned) birds will cause them to regain consciousness, causing them to suffer from stress and pain during bleeding, and in some cases, the birds will be scalded in hot water while they are still alive. This is one of the main reasons why some scholars do not prefer the electrical water bath stunning method. Suppose the bird's death was due to the heat generated from the scalding tank. In that case, the birds are not fit/accepted to be consumed by Muslims because it violates the main principle of halal slaughtering, in which animals should have died because of the cut made during slaughtering and not by any other means.

Hindle et al. (2010) suggested that water bath stunning should induce unconsciousness and insensibility in birds immediately within 1 s of application. There are a few suggestions on the minimum duration of unconsciousness for effective stunning. Raj (2006) suggested that water bath stunning should be able to induce at least 40 to 60 s (Raj, 2006; Hindle et al., 2010; EFSA, 2012). Electrical frequency and the time interval between stunning and neck cut play a vital role in the effectiveness of electrical stunning (Sabow et al., 2017). A delay in the neck-cutting process may expose the birds to pain after they regain consciousness. Lambooij and Hindle (2018) and Nielsen et al. (2019) reported that each bird might receive a different amount of current due to the variety of weight and size of the birds, where some of the birds may not receive enough current to induce an epileptic seizure in their brain while others may receive greater current than needed resulting into poor carcass and meat quality production. Gibson et al. (2016) also reported that the duration of unconsciousness is shorter in laying hens compared to broiler chickens.

SPIRITUAL QUALITY ASPECTS OF ELECTRICAL STUNNING

Spiritual quality has been the basis for accepting food products for some religious communities. The same goes for the electrical water bath stunning procedure, which must comply with all the requirements and guidelines stated by the local religious authorities. The water bath electrical stunning procedure aims to induce reversible insensibility in birds. If a bird is subjected to a stunning procedure and dies due to the stunning effect, the meat is no longer fit for Muslim consumption. Stunning an animal would cause the animal to be slaughtered without pain, suffering, and distress as long as the neck-cutting procedure is performed during the bird's unconscious state. The most common problem occurring in an electrical water bath stunning system that would affect the spiritual quality is the prevalence of overstunned and understunned birds.

ETHICAL QUALITY ASPECTS OF ELECTRICAL STUNNING

Electrical stunning has been implemented in a halal poultry processing line because it can render the animal unconscious while simultaneously being able to abide by the halal regulations. Shahdan et al. (2016) stated that electrical stunning in halal processing plants should not

1. Interfere with the neck-cutting process,
2. Interfere with the blood flowing after neck cutting,
3. Lead to death before neck cutting, and
4. Give rise to further pain or stress.

If done correctly, stunning would be the best method of managing animal welfare. However, if the electrical current used during the procedure is insufficient, it can ultimately lead to more unnecessary pain than conventional practice.

Conventionally, chickens slaughtered without a stunning system will be inverted and suspended on shackles, which causes the birds to struggle vigorously and flap their wings, thus resulting in pain and distress (Zulkifli et al., 2019). Similarly, chickens are shackled to ease the stunning and slaughtering process; however, if the birds do not lose consciousness due to an understunned incident, the birds will be subjected to stress from both 1) the shackling upside-down position (Lambooij et al., 2014), and 2) the pain through the neck-cutting process and bleeding (Nielsen et al., 2019).

Stress, Pain, and Distress

One of the major concerns for consumers nowadays is the pain and stress suffered by an animal processed for human consumption. How an animal is treated is important because it affects the animal welfare and the quality of meat produced.

Table 2. Application of electrical water bath stunning in poultry.

Species	Electrical water bath	Electrical inputs	Salient findings	References
Broilers, 6-wk age, 2.2 kg	Head only, 1.5−2.5 mS/cm conductivity	50 Hz sinusoid current, 7.5−10 V/cm rms for behavioral and 10−25 V/cm rms for EEG recording, 1 s	• Immediate unconsciousness and increasing electrical voltage extend the unconsciousness duration • A 25−30 mA AC current at 2,000 Hz current from shackle to water bath suppressed wing flapping • Suppression of EEG signals for 30 s, so enough to facilitate humane slaughter	Lines et al., 2011a
Broiler, male, 47 d, 3.49 kg		50 Hz sinusoid current, 17.5−19 V/cm rms, 7 ± 1.5 s	• A 36 ± 1.5 mA at 2,000 Hz sinusoidal current from shackle to water bath prevented wing flapping • Significantly lower carcass damage than stunning at higher electric current • Carcass quality (hemorrhage in wing, shoulder, and breast fillet and broken bones in pectoral region) similar to stunning current used in commercial plants (63 mA, 610 Hz pDC)	Lines et al., 2011b
Broilers, Ross, 45 d, 3.2 kg	Commercial water bath stunning	150−200 mA, 51−60, 61−80, and 81−100 V	• Significant (P < 0.001) effect of electrical parameters on cloacal reflex (8 s for 96% broilers) and palpebral reflex (12 s for 80% broilers) • Breathing response after 27 s after stunning • Bruises on wings significantly (P < 0.001) affected by voltage	Novoa et al., 2019
Cobb mixed sex, 44 d	Stunner under pulsed direct current	100−700 Hz, 40−120 V, 14 s	• Less incidences of PSE in stunned poultry (25% in stunned vs. 54.14% in unstunned) • 120 V and 700 Hz as most efficient for inhibition of PSE	Kissel et al., 2015
Culled layer hens	Variable voltage−constant current stunner	100 mA, 100−1,500 Hz sine wave AC, 3 s	• 100 mA at 100−200 Hz induces epileptiform activity • Stunning at 400, 800 or 1,500 Hz failed to induces epileptiform response and failed to stun satisfactorily • A greater current than 100 mA should be applied if 400 Hz or higher sine wave AC applied	Raj and O'Callaghan, 2004
Ross 208, 2 kg, 37 d	-	40 V, 10 s	• Better carcass quality of stunned birds as compared to unstunned birds due to decreased broken bones, red wings and bleeding spots	Shafik et al., 2021
Broiler, 3.75−4.2 kg	-	30−220 V, 200−750 Hz, 4 s	• High stunning frequencies causes lower incidences of lesions in carcasses but need higher current intensities to be effective • 750 Hz frequency and 200 mA current in water bath appropriate for poultry welfare	Girasole et al., 2015
Broilers, organic, heavy	-	Electronarcosis	• High intensity (>100 Hz) resulted in higher deads • Lower impedance in older birds	Mellier et al., 2017

(*continued*)

Table 2 (*Continued*)

Species	Electrical water bath	Electrical inputs	Salient findings	References
Geese, Yangzhou 92-days old, 3.8 kg	Water with 1% NaCl	High-frequency current, 20−100 mA, 500 Hz, 10 s	• 40 mA at 500 Hz for 10 s alleviates stunning stress and lipid oxidation in geese with maximum serum uric acid and urea • Decreased ($P < 0.01$) serum ACTH and CK at 40 mA current as compared to 70 mA and 100 mA	Xu et al., 2021
		High-frequency current of 500 Hz, 30−120 V, 20−100 mA, 10 s	• A 60 V, 40 mA, 500 Hz for 10 s per goose improved lipid oxidative stability and antioxidant capacity in the livers • Highest ($P < 0.05$) MDA at 120 V at d 0	Zhang et al., 2020
Broilers	Head-to-cloaca (HTC) vs. conventional water bath	70 mA/70 Hz; 100 mA/100 Hz; 1.5 s	• Birds effectively stunned by Head-t-cloaca stunning with 70 mA or 100 mA for 1.5 s • Significant ($P < 0.05$) decreased heart rate after stunning and recovered after 60 s • Better carcass quality (muscle blood splashes in fillets and legs) and lower ($P < 0.01$) shear force in the HTC stunning	Lambooij et al., 2012
Broilers	DC and DC+AC current stunner	15 V and 25 V DC for 10 s; 100, 110 and 120 V AC for 5 s	• Both stunning causes nonrecoverable unconsciousness useful in stun-to-death stunning • No significant difference between carcass and meat quality parameters	Bourassa et al., 2017
Broiler, Ross 708, 6−8 wk, 3.2−4.0 kg		53−80 V−1,400 Hz, 150−190 V−1,400 Hz 15 s	• Weight of broilers important parameters for applying appropriate electrical parameters for effective stunning and poultry welfare	Smaldone et al., 2021
Broilers, light (1.74 kg)/ medium (2.6 kg) and heavy (3.4 kg)		90 mA/bird, 400 Hz (old EU regulation) and 150 mA/bird, 400 Hz (New EU regulation)	• Higher current flow as per new EU regulations 1,099/2,009 increases hemorrhages and maintain meat quality • Significant ($P < 0.001$) higher hemorrhages in new group as compared to old group • Meat quality except drip (lower in new group) were not affected	Sirri et al., 2017
Commercial broilers 35−40 d, 1.7−2.3 kg	Commercial slaughter lines, UK	Pulse DC and sine wave AC; neck cut after 5−7 s	• Assessment of stunning efficiency through corneal reflex, rhythmic breathing, head shake and escape behavior • Electric water bath did not meet the recommended current and frequencies for effective stunning	Anastasov and Wotton, 2012
Broiler, Ross, male, 2.96 kg, 42-days old	DC/AC waveform, 10−350 V rms, 20−3,000 Hz	220 mA with 1,100 Hz; 6,600 Hz hybrid frequency waveform	• Hybrid frequency waveform induces epileptic form in birds EEG and produced better meat quality while ensuring better poultry welfare	La Vega et al., 2021
Broiler, Cobb, 48 d, 2.76 kg	Commercial (70 V, 100 mA)	300 and 650 Hz, DC and AC waveform	• Stunning at higher frequency (650 Hz) render efficient unconsciousness and better meat quality	Siqueira et al., 2017

(*continued*)

Table 2 (*Continued*)

Species	Electrical water bath	Electrical inputs	Salient findings	References
Broiler	Commercial constant voltage stunner	150−250 mA; 200−1,200 Hz	• Abolition of corneal reflex at 20 s poststun is affected by frequency ($P < 0.0004$), rms current ($P < 0.0001$) and interaction between frequency and stunning current ($P < 0.0001$) • Stunning at frequency higher than 600 Hz not recommended with 150 mA current	Girasole et al., 2016
Broiler, Ross, male (2.6 kg) and female (2.3 kg)	Plastic basin with metal plate, water conductivity-4 mS/cm conductivity	50 Hz and 70 Hz AC, 70 Hz DC, 60−80 V, 4 s	Lower stunning efficiency for female birds Low stunning efficiency of pulsed DC could be due to short stunning time (4 s) Pulsed DC stunning has lower incidences of induction of death	Prinz et al., 2012
Broiler, Arbor Acres, 2−2.5 kg, 45 d	Water with 1% NaCl	LS-15 V, 750 Hz for 10 s; MS-50 V, 50 Hz for 10 s HS-100 V, 50 Hz, for 5 s	• Stunning methods have no effect on meat color, cooking loss, pressing loss and ultimate pH • Nonstunned and MS group showed increased ($P < 0.05$) corticosterone, initial rate of glycolysis, drip loss and decreased ($P < 0.05$) initial muscle pH, shear force as compared to LS and HS group.	Huang et al., 2014
Broiler, hen, and ducks	Purpose built water bath stunner, IMARES	Broilers- 45−444 mA, 100−400 V; Hen- 40−219 mA, 150−300 V, 50−1,000 Hz Ducks-64−362 mA, 50−400 Hz; 150−400 V	• Effective stunning using water bath stunning produced blood splashing in broilers. • Hen requires lower current for effective stunning and also individual variations in electrical impedance in birds • Body weight and bird type did not affect the occurrence of effective stun	Hindle et al., 2010

Hormonal Indicators

Hormonal indicators can be used as a guide for stress, pain, and distress. The level of blood biochemical parameters such as thyroid hormones, adrenaline, noradrenaline, and corticosterone are very useful in evaluating poultry response to stress (Bedanova et al., 2007; Ismail et al., 2019; Zulkifli et al., 2019). A similar claim was suggested by Blas (2015), in which he suggested that the aforementioned blood biochemical parameters from the blood plasma of birds can be used to measure their stress status (Table 3).

Adrenaline

Adrenaline can be used as one of the indicators of physiological changes and thus indicating whether an animal is suffering from pain or stress. The response to acute stress brings about a cascade of physiological reactions in an animal; thus, the nervous sympathetic-adrenomedullary system is triggered, which later responds by producing catecholamines (Mellor and Stafford, 2000). Similarly, a study by Linares et al. (2008) suggested that lamb stunned via electrical procedure showed higher adrenaline concentration compared to animals subjected to gas stunning.

Noradrenaline

Noradrenaline or norepinephrine is a neurotransmitter from sympathetic nerves responsible for tonic and reflexive cardiovascular tone changes. It is an organic chemical in the catecholamine family that acts as a hormone and neurotransmitter in the brain and body.

The study conducted by Zulkifli et al. (2013) showed that the concentration of plasma noradrenaline in animals subjected to high-power nonpenetrating mechanical stun was significantly increased. However, Linares et al. (2008) reported that noradrenaline concentration in animals remained unaffected by both types of stunning procedure and slaughter weight.

Corticosterone

Corticosterone is the primary hormone of the pituitary adrenocortical axis secreted by the avian adrenal

Table 3. Concentrations of corticosterone and cortisol as affected by various stressors in poultry.

Animal	Stressors	Hormone	Concentration		Author
Broiler Chicken (Cobb500), 38-days old, mix sex	Control (before stun), stunning (50 V, 400 Hz)	Corticosterone	5.9 ng/mL (before stunning)	14.14 ng/mL (after slaughter)	Zulkifli et al., 2019
Broiler, chicken, male, Ross	Cyclic heat stress (31−32°C) for 8 h/d	Feather corticosterone	7.38 pg/mL (control)	16.65 pg/mL (heat stressed)	Kim et al., 2021
Broiler chicken, yellow feathered	Road transport (0.5−3 h)	Corticosterone	63 μg/L (0 h of transport)	130.2 μg/L (1 h of transport)	Gou et al., 2021
Broiler, chicken	Road transport 6 h, open vs. environment-controlled housing system	Corticosterone	3.4 ng/mL (0 h transport)	15.2 ng/mL (6 h transport)	Al-Aqil and Zulkifli, 2009
Broiler Chicken (Cobb500), 42-days old, male	Shackling and cone restraining	Corticosterone	1.89 ng/mL (cone restraining)	1.94 ng/mL (shackling)	Ismail et al., 2019
Geese (Yangzhou), 28-days old, male	Different electrical stunning current (Control—no stun, 20 mA, 40 mA, 70 mA, 100 mA)	Cortisol	20.49 ng/mL (control—no stun)	18.48 ng/mL (70 mA)	Xu et al., 2021
Wumeng black bone chicken, 180-days old, female	Slaughter with stunning with 50 Hz, 50 V, and slaughter without stunning	Cortisol	273.51 pg/mL (stunned)	504.29 pg/mL (no stun)	Li et al., 2022

cortex in response to environmental challenges, and it has an important function in metabolism and in stress and adaptation (Boer and Koolhaas, 2017). Stress may occur as early as during crating procedure and transportation to the processing plant, way before it reaches the point of stunning (HSA, 2015). Besides that, shackling procedure and shackle line movement before slaughter had caused the level of corticosterone concentration in birds to increase, indicating stress (Debut et al., 2005; Bedanova et al., 2007).

In a study, Zulkifli et al. (2019) revealed that the plasma corticosterone concentration is higher after stunning than the corticosterone after air ageing and shackling. Bedanova et al. (2007) also reported that corticosterone concentration increases as the shackling period increases. The authors also found a 4- to 9-fold increase in corticosterone levels after 60 s and 120 s of the shackling period, respectively. Shackling birds under 60 s would not elevate the corticosterone concentration in birds (Bedanova et al., 2007). As a result, corticosterone level does not fluctuate in response to stress since the shackling period is less than 30 s (Zulkifli et al., 2019). Huang et al. (2014a) reported that the plasma corticosterone level was recorded higher in unstunned birds and birds subjected to low stunning treatment (15 V, 13−15 mA, 750 Hz pulse wave DC, 10 s) compared to middle stunning (50 V, 48−52 mA, 50 Hz sine wave AC, 10 s) and high stunning treatment (100 V, 106−110 mA, 50 Hz wave AC).

Biochemical Indicators

Like hormonal indicators, biochemical parameters can be used as physiological indicators to measure stress and pain levels in birds (Hrabčáková et al., 2014). The severity of stress and pain endured by an animal subjected to pain stimulus will be reflected in the changes in blood biochemical composition (Zheng et al., 2020). The dynamics of hormonal indicators such as corticosterone and blood biochemical parameters (glucose and lactate levels) showed a similar pattern, thus providing similar information regarding stress and pain levels in birds (Bedanova et al., 2007) (Table 4).

Blood Glucose Level

Glucose values can be used as an indirect indicator of stress (Mota-Rojas et al., 2007). When a stress stimulus is introduced to an animal, the body will secret catecholamines and glucocorticoids, thus resulting in increased glucose levels (Shaw and Tume, 1992). Glucose quantification can be a useful indicator of animal stress due to the relation between glucose and energy metabolism, especially during stressful conditions. A previous study by Mota-Rojas et al. (2012) reported that gas stunning had more impact on physiological parameters than stress due to transportation. Gas stunning had significantly increased carbon dioxide, glucose, and lactate values. The author also reported a positive correlation between glucose level, oxygen concentration, and temperature. Riggs et al. (2023), in their study, had shown that broilers that undergo controlled atmosphere stunning resulted in a higher blood glucose concentration than electrical stunning. On the contrary, a lower blood glucose level was obtained for broilers stunned using gas stunning compared to electrical stunning from a study performed by Pinto et al. (2016). The main difference between both studies is the voltage and frequency used, in which Riggs et al. (2023) performed the study using a high-frequency and low-voltage procedure (12−38 V, ≥400 Hz). In contrast, Pinto et al. (2016) adopted a high-voltage, low-frequency procedure (220 V, 60 Hz).

Table 4. Various biochemical parameters as affected by electric stunning in poultry.

Species	Stunning protocols	Biochemical indicators	References
Broilers chickens (live weight—2 kg)	Electric stunning (20 mA/birds for 12 s) and CAS (increased CO_2 concentration from 20 to 85% in 5 phases within 5 min with O_2 added to achieve 21% in first 90 s)	• The blood glucose concentration of birds was not significantly different at large (272 vs. 284 mg/dL, $P = 0.2646$) or before stunning (283 vs. 274 mg/dL, $P = 0.6425$) • CAS birds showed significantly higher ($P < 0.0001$) blood glucose (418 mg/dL) as compared to blood glucose in electrically stunned birds (259 mg/dL) immediately after stunning and neck cut	Riggs et al., 2023
Broilers (Cobbs-500, 42-days old)	High-voltage−low-frequency electric stunning (220 V AC, 120 mA, 60 Hz for 5 s), CO_2 stunning, or a mixture of 75% CO_2 + 25% Ar	• Significant increase in blood glucose levels (337.65 mg/dL) in electrically stunned birds as compared to that of CO_2-atmosphere stunned (315.7 mg/dL) and control (305.95 mg/dL) birds • Significantly higher ($P < 0.05$) levels of blood lactate (mmol/L) in electrically stunned birds (7.8) vs. control (5.4)	Pinto et al., 2016)
Broilers (Cobbs, 48-days old, 2.76 kg)	Electric stunning (70 V, 100 mA, 300−650 Hz, AC, and DC current)	• Decreased Na levels at 300 Hz—DC group • AC waveform decreased plasma glucose and DC decreased CK • Blood glucose and CK were higher whereas K was lower in the blood of birds stunned at 300 Hz	Siqueira et al., 2017
Chickens (Women black bone, female, 180-days old)	Medium-voltage−low-frequency electric stunning (50 V, 48−52 mA, 50 Hz for 10 s) vs. unstunned control	• Blood of stunned chicken showed significant ($P < 0.05$) cortisol levels as compared to those of unstunned chickens	Li et al., 2022
Broilers (Arbor Acres, male, 49-days old, 2.5 kg)	Electric stunning (35−65 V, 47−86 mA, 400−1,000 Hz for 18 s) and gas stunning (40−60% CO_2 for 90 s)	• Stunning caused changes in blood variables except for blood glucose • Plasma pH decreased ($P < 0.01$) in stunned groups except birds stunned at 65 V, 86 mA, and 1,000 Hz • No consistent differences in other blood variables (plasma uric acid, lactate, and urea nitrogen)	Xu et al., 2011
Broilers (Arbor Acres, Mixed sex, 45-days old, 2−2.5 kg)	Low voltage (15 V at 750 Hz for 10 s) mid voltage (50 V at 50 Hz for 10 s) and high voltage (00 V at 50 Hz for 5 s) stunning	• No significant ($P > 0.05$) effect on plasma glucose and lactate levels under different stunning methods used	Huang et al., 2014

Control, slaughtered without stunning; *CAS, controlled atmosphere stunning; CO_2, carbon dioxide; O_2, oxygen; AC, alternate current; DC, direct current; CK, creatine kinase.

Soleimani and Zulkifli (2010) reported that heat treatment up to 36°C for 3 h had significantly increased blood glucose levels in different types of birds (Red jungle fowl, Village fowl, and commercial broilers).

In other species, the blood glucose level in rabbits subjected to gas stunning was higher than in unstunned rabbits (Nakyinsige et al., 2014). Various studies have shown that critical blood constituents, such as catecholamines, lactate, glucose, calcium, magnesium, and proteins, increase after an animal is slaughtered (Hartung et al., 2008; Becerril-Herrera et al., 2009). Stress originating from transportation has been reported to have a significant effect on blood glucose levels; in which cattle transported less than 200 km showed higher glucose levels compared to cattle transported for more than 400 km (Chulayo et al., 2016). The authors noted that animals stunned more than once had a lower glucose level than those stunned only once.

Lactate

An increase in blood lactate due to anaerobic glycolysis will be observed in animals after slaughter due to the deprivation of adequate oxygen level at the tissue level, in which the end product of the process, which is pyruvate is reduced to lactate by the liver enzyme lactate dehydrogenase. In a live animal, lactate produced in the muscle can be transported by the blood to the liver and converted to glucose through a process known as the Cori Cycle using the enzyme lactate dehydrogenase. However, this is impossible in the dead animal because of the lack of blood circulation. Therefore, lactic acid and lactate accumulate in muscle and the bloodstream.

The amount of glycogen reserves in animals during slaughter greatly affects the amount of lactic acid produced during rigor development (Rosenvold et al., 2001; Nakyinsige et al., 2014). Determination of lactate levels can be used to assess an animal's stress level before, during, and after stunning (Hambrecht et al., 2004; Nowak et al., 2007). Grandin (1998) also observed that animals slaughtered without stunning had been associated with a high lactate level due to anaerobic glycolysis.

Studies on the effect of preslaughter stress on pigs and levels of lactate after the slaughter had shown that they were correlated with each other (Hambrecht et al., 2004; Nowak et al., 2007). Higher lactate levels and lower muscle pH values were recorded in pigs that suffered from stress compared to the control group (Nowak et al., 2007). However, Nakyinsige et al. (2014) reported that no significant difference in lactate level was observed between rabbits slaughtered with and without stunning. A study by Becerril-Herrera et al. (2009) showed a positive correlation between hematocrit percentage and lactate concentrations in pigs subjected to gas stunning.

Electroencephalogram Indicators

EEG is a method used to measure the brain's electrical activity (using small metal disk electrodes attached to the scalp). It is commonly used to detect body response to a specific external input. As an electrical water bath stunning system utilizes the electrical current to render an animal unconscious, EEG can be used to measure brain activity owing to its capability to measure even if the animal is unconscious. EEG can be used to determine the effectiveness of the electrical currents applied by observing the unconscious state of the birds after stunning as the brain loses its function to respond to any stimulus (Raj and Tserveni-Gousi, 2000).

An improper stunning practice may cause the animal stress and pain. Hartung et al. (2002) demonstrated that pig stunning using 80% of CO_2 gas for 70 s is insufficient in rendering the animal unconscious. If the current applied to the animal brain is sufficient, it can induce an epileptic seizure, which can be viewed using an EEG (Raj, 2006; EFSA, 2012; HSA, 2015). Knowledge of the physiological response of animals toward the electrical stunning applied may help us to combat any issues regarding the ineffectiveness of stunning practiced (Lambooij and Hindle, 2018).

The characteristics of epileptic activity were affected by the loss of blood pressure and decreased oxygen supply to the brain due to heart failure (Lambooij and Gerritzen, 2007). European Food Safety Authority EFSA (2012) and HSA (2015) stated that the expression of epileptic activity and the degree of EEG suppression is associated with the combinations of different electrical parameters (i.e., whether a bird immediately becomes and remains unconscious for long enough). Prinz et al. (2012) observed that using high amplitude, low frequency, and sine waves of AC during stunning is more effective than other waveforms in generating epileptic seizures and suppressing EEG.

Acute Phase Proteins

Acute phase proteins (**APP**) are synthesized in the liver and are associated with inflammation or infection occurring in birds (O'Reilly et al., 2018). The APP's functions are as inhibitors of protease, enzymes, proteins transport, proteins coagulation, and modulators (Zulkifli et al., 2018). The plasma APP levels increase during inflammation, tissue injury, stress, and immunological disorders to provide a nonspecific immune defense. These are categorized into 2 groups: positive APPs and negative APPs. The positive APPs levels increase in challenging conditions such as ceruloplasmin, C-reactive proteins (**CRP**), haptoglobin (**HP**), fibrinogen, serum amyloid A (**SAA**), and alpha-1 acid glycoproteins. The negative APPs levels decrease under challenging conditions such as albumin transferrin (Murata, 2007).

C-Reactive Proteins

CRP is a phylogenetically highly conserved plasma protein that responds to inflammation. The concentration of CRP will increase with inflammation, infection, and tissue damage (Pepys and Hirschfield, 2003; Sohail et al., 2010). As a result, this special feature is commonly used to determine the extent of injury in the muscle after an external pain stimulus is given . Hemorrhaging is the most common meat quality problem associated with electrical stunning. There is still a lack of information about the relationship between CRP and electrical stunning procedure. However, it is well known that an effective and efficient stunning procedure may decrease movement and struggle during neck cutting and bleeding, thus reducing the number of injuries and inflammation compared to unstunned animals.

A previous study by Sohail et al. (2010) showed that broilers subjected to heat stress have a higher amount of CRP than the normal thermoneutral group. Jahanian et al. (2019) reported that broiler chickens exposed to aflatoxin had a higher relative abundance of CRP than the control group.

Heat Shock Proteins

Heat shock proteins (**HSP**) are a set of proteins produced by animals as a response mechanism to physical, chemical, or biological stresses, including heat exposure. When animals are experiencing stress, the HSP amount in the body increases rapidly to protect the organs and cells from damage (Gu et al., 2012; Zheng et al., 2020). They are 5 types of HSP categorized based on their molecular weights, viz., HSP60, HSP70, HSP90, HSP100, and small HSPs (**sHSPs**) (Xing et al., 2018). Zheng et al. (2020) observed that transportation does not affect the expression of HSP70 in the liver of broiler chickens due to the degree of intensity and duration of transportation that produce insufficient stress to induce the expression of HSP70. Gu et al. (2012) reported that the expression of HPS70 is higher as exposure to heat stress increases.

EATING QUALITY ASPECTS OF ELECTRICAL STUNNING

Consumers' demand for high-quality meat products has been increasingly popular for the past few decades. Mir et al. (2017) stated that there are a few attributes that were taken to account when judging the quality of meat, such as sensory attributes, which consist of color, texture, juiciness, taste, odor, and texture, next nutritional composition, which are fat content, fatty acid profile, protein percentage, minerals, vitamins, and technical parameters such as pH, WHC, and thawing loss.

General Concept of Meat Quality

Consumers' perceptions of meat quality may differ from what producers perceive. Various factors such as demographic background, economic status, ethnicity and culture, individual belief and ideologies, and final product presentation affect the perception of meat quality (Fayemi and Muchenje, 2012; Farouk et al., 2014).

However, it is worth noting that the quality of animal meat cannot be improved as much after they have been slaughtered. Thus, processing techniques and quality retention must be optimized throughout the production line. For instance, improper preslaughter handling of animals across various production chains, including stunning, could have various adverse effects on carcass and meat quality (Nakyinsige et al., 2014; Sabow et al., 2017; Imlan et al., 2020), thus causing degradation in meat quality and prevalence of pale, soft, exudates (**PSE**) and DFD meat.

pH

pH may directly or indirectly affect other meat quality attributes such as tenderness, WHC, color, juiciness, and shelf life (Mir et al., 2017; Zheng et al., 2020). The physical and psychological stress of the birds affected the amount of glycogen in the muscles, which reflected the pH of the meat. Mir et al. (2017) reported that WHC in broiler breast meat is higher in meat with higher pH than meat with lower pH. Protein denaturation due to postmortem pH decline will cause WHC to decrease. This will cause PSE meat, affecting its texture (Siqueira et al., 2017).

Both the electrical inputs used during stunning procedures and the inverted position of the birds during shackling affected the carcass and meat quality. However, meat quality is not solely impacted by the processes found in a poultry processing plant. For instance, during the transportation of the birds to the slaughterhouse, the birds are exposed to stressful environments such as heat stress, noise disturbance, overcrowding within the crates, the movement of the vehicle, and others (Chambers et al., 2001; Adzitey, 2011). As a result, birds suffered long-term stress throughout the travel duration, which would worsen if the distance between the farm and the processing plant was huge. As they struggle to cope with the harsh environment, they tend to use more energy to consume the glycogen stored as energy in the muscle. The glycogen concentration in muscle will be depleted, causing less production of lactic acid accumulation in muscle after the animal is slaughtered, thus increasing the pH value of meat. This affects WHC, thus, may lead to the production of DFD.

Moreover, acute exposure to stress may result in PSE meat as the pH of the muscle rapidly declines. Zheng et al. (2020) reported that as transportation increases, the drip loss of the meat after 24 h increases. In conclusion, high-graded meat is attainable, but it needs much effort due to the various factors that could easily affect the quality of the end product.

Tenderness

Current poultry processing procedures are generally divided into conventional commercial and, religious, traditional processing. Commercially produced meat has incorporated stunning procedures during production, whereas traditional religious processing opposed the use of stunning in their production process. The dispute surrounding both methods still needs to be resolved. However, the upsurge of numerous studies has proven that stunning, if carried out efficiently and effectively, could improve eating, ethical, and spiritual quality.

Tenderness is perceived as the most important organoleptic trait for meat quality (Hayat et al., 2021), and it is categorized as one of the intrinsic eating qualities of meat (Farouk et al., 2014). Stunning techniques, if not efficiently and effectively employed, could influence tenderness, thus resulting in poor eating quality (Thompson, 2002). When applied correctly, stunning will improve meet tenderness (Contreras and Beraquet, 2001; Nakyinsige et al., 2014; Lokman et al., 2017; Sabow et al., 2017). However, Sirri et al. (2017) reported that nonsignificant difference in shear force for broilers subjected to 90 mA and 150 mA electrical currents. A study by Huang et al. (2014a) reported that unstunned broilers have lower shear force values compared to the electrically stunned group. Xu et al. (2011) reported that different electrical stunning voltages and frequencies only affected the Pectoralis major muscle, not the Musculus iliofibularis.

Water-Holding Capacity

The ability of a postmortem muscle to retain water when subjected to an external stimulus such as pressure, gravity, and heating is known as WHC. WHC plays an important role in determining the final product quality in terms of visual representation, final weight, juiciness, tenderness, and overall acceptability. Mir et al. (2017) reported that WHC in broiler breast meat is higher in meat with higher pH than meat with lower pH. Protein denaturation due to postmortem pH decline will cause WHC to decrease. This will cause PSE meat, affecting its texture (Siqueira et al., 2017).

A high WHC is related to the juiciness of the meat. However, achieving maximum juiciness is a tricky endeavor because various factors influence the juiciness of the meat. Some factors are animal species, rearing system, feeding nutrition, age and maturity of an animal at slaughter, cooking method, slaughter management, and meat processing. Xu et al. (2011) stated that applying a high-frequency stunning procedure will positively influence the WHC of meat. Siqueira et al. (2017) and Huang et al. (2014a) in their study had also stated that WHC was higher when the birds were stunned at 650 Hz and 750 Hz, respectively.

However, Sirri et al. (2017) reported that broiler breast meat subjected to 150 mA of electrical current had lower drip loss than those subjected to 90 mA. Huang et al. (2017) reported that broiler chickens stunned using different voltages showed no significant difference in cooking loss. However, they also reported that drip loss was higher in birds stunned at the lowest voltage (5 V). Similar results were also reported by Xu et al. (2011), where broiler chickens subjected to different electrical voltage and frequency did not show any significant difference between them.

Color

Color plays an important role in the consumer's decision to purchase meat. Visually appealing meat may influence the consumer to purchase the product. In the eyes of the consumer, the wholesomeness of meat at the point of sale relies greatly on fresh meat color (Suman and Joseph, 2013). Meat color is primarily influenced by the chemical state of sarcoplasmic heme protein called myoglobin. Myoglobin may exist either in the form of metmyoglobin or oxymyoglobin, which, in both forms, has a profound effect on the color of meat. Aside from the presence of myoglobin, light reflection can also be the main factor in influencing color (Hayat et al., 2021). Degradation of muscle protein will disrupt muscle stability, thus resulting in the reduction of WHC. More water means more light reflection, thus causing the meat to appear paler (Hayat et al., 2021). However, disruption of muscle stability is mostly associated with cold storage and the thawing procedure rather than stunning.

A recent study reported that an electrically stunned broiler has no significant difference in lightness, redness, and yellowness compared to unstunned broilers (Huang et al., 2014). Huang et al. (2017) reported that broiler chickens subjected to different stunning voltages (5 V, 15 V, 25 V, 35 V, 45 V) had no significant differences between all treatments. Similar results were obtained by Xu et al. (2011), in which no significant difference in color was observed in both Pectoralis major and Musculus iliofiburalis muscles subjected to different electrical voltage and frequencies during stunning.

Bleeding Efficiency

In poultry processing, the term bleeding is known as the process of natural blood removal after neck cutting is performed. The objective of bleeding in the slaughter process is to induce irreversibility of sensibility. Sufficient bleeding time will improve meat quality, longer shelf life, and reduce microbial growth (Sabow et al., 2017). Various factors can influence the rate and effectiveness of bleeding. Some of the factors are as follows: cardiac arrest during stunning, severed vessels, vasoconstriction or vasodilatation in the capillary network, influence and size of the sticking wound, carcass orientation (vertical or horizontal), clonic movements that cause blood to flow toward the sticking wound, and tonic muscle contractions that compress blood capillaries and vessels (Gregory, 2005), stunning durations (McNeal and Fletcher, 2003), preslaughter handling (stunning or no stunning) (Gregory, 2005; Kissel et al., 2015), and hemorrhagic conditions (Kranen et al., 1996). EFSA (2012) and HSA (2015) reported that the birds might take longer to bleed out if the neck cut process was not done properly, and the bleeding rate and blood retention in engorged vessels in the wing, breast, and muscles are affected by the time of neck cutting.

The factors mentioned above are strongly related to the amount of frequency and voltage used during stunning (Gregory, 2005). Ali et al. (2007) stated that there is still indecisiveness in the effect of low and high voltage of stunning on the bleed-out rate. However, Contreras and Beraquet (2001) reported that the rate of bleed-out is higher when using a high frequency of stunning.

Ali et al. (2007) found that the bleeding efficiency can be over 50% when the birds are stunned for 10 s at moderate stunning voltages (53−63 V of alternating current (**AC**)). However, the authors reported that stunning at low voltages (0−23 V AC) and high voltages (100 −193 V AC) resulted in poor bleeding as low as 40%. Contreras and Beraquet (2001) experimented with measuring the influence of stunning voltage (20, 40, 80, 100 V, and no stunning) at 60 Hz of frequency on blood loss. They observed that stunning at 40 V resulted in a 55.3% higher blood loss than others, while the unstunned broilers have the lowest blood loss, 27.2%.

Glycogen Content

Glycogen stored in the animals' muscles will be converted into lactic acid, producing tasteful, tender, good quality, and colored meat. Stress during preslaughter handling and slaughtering procedures resulted in lactic acid in the muscle, thus reducing meat quality (Chambers et al., 2001; Ali et al., 2008; Gregory, 2008; Adzitey, 2011). Inappropriate action during preslaughter handling may cause the development of meat abnormalities in the carcasses, such as PSE or DFD. Ali et al. (2008) stated that the initial pH would drop as the birds struggle on the shackle, increasing redness in breast meat. Xu et al. (2011) reported that the glycogen concentration in broilers subjected to 35 V of electrical current is higher than in broilers stunned at 65 V. Similar trend was observed when broiler chickens were stunned at a lower frequency (160 Hz); it exhibited a higher glycogen content compared to broilers subjected to 1,000 Hz of stunning frequency.

Carcass Quality

Previous studies have proven that stunning procedures in an electrical water bath system affected bird welfare and meat and carcass quality attributes (Joseph et al., 2013; Berg and Raj, 2015). Studies have also mentioned that to maintain meat quality, a variety combination of the waveform (alternating and direct current) and frequency are used to produce a stunning result (EFSA, 2004; Prinz, 2009; HSA, 2015). Hindle et al. (2010) noted that high voltage during stunning will produce a higher current, thus increasing the probability of hemorrhages. Gregory (2005) suggested that by using the stunning high-frequency procedure, hemorrhage occurrence in meat can be reduced significantly as less muscle contraction during stunning. Hindle et al. (2010)

reported that the occurrence of blood spots in broiler carcasses is 67% when stunning at 50 Hz with currents ranging from 45 to 240 mA, while 35% of blood spots were found among the broiler carcasses after being stunned at 400 Hz with currents ranging between 150 and 250 mA. Girasole et al. (2015) stated that muscle contraction increases when low frequencies (50−60 Hz) were used during stunning, resulting in small blood vessels rupturing rapidly. The quality defects in broiler carcasses, such as breast muscle hemorrhage, cardiac arrest, and broken bones, are commonly seen in birds when stunned with 120 mA current and at low frequencies (50−60 Hz) (Lambooij and Gerritzen, 2007; Hindle et al., 2010). Lambooij and Hindle (2018) suggested that the birds stunned at <200, 200 to 400, and >400 Hz should receive a minimum current of 100 mA, 150 mA, and 200 mA, respectively, to encounter quality defects in broiler chicken.

PROSPECTS AND CONCLUSIONS

Nowadays, the application of electrical water bath stunning in the poultry industry has been associated with spiritual, ethical, and technological quality traits. Spiritual quality can be defined as the need to meet the requirement of religion and one's feelings. Stunning practice should be executed in line with guidelines stated in the religion's regulations for the believers to gain spiritual quality. On the other hand, the major issue in ethical quality is considered to produce maximum ethical practice in meat production, and technological quality is related to the quality of the products that match their needs. These 3 key aspects need to be considered when considering the application of an electrical water bath stunning system as it can relate to animal welfare concerns and directly affect the meat quality spiritually and technically.

The fluctuation in demand for halal and kosher meat has led the poultry industry to enter a new phase, in which, spiritual quality shall be considered if any technological advancement is to be applied throughout the production. Although, spiritual quality is the primary consideration in meat acceptance for both Muslims and the Jewish community, ethical and eating quality shall also be regulated to their best conditions. Failure to do so may result in the downgrading of meat and downstream meat products such as sausages, nuggets, and burger patties, which consequently lead to economic losses. Through earlier scientific studies, the electrical water bath stunning system has been positively implicated in religious, ethical, and eating quality. However, these are only attainable if the system is employed effectively. The fact that high-frequency electrical water bath stunning renders unconsciousness in birds without causing cardiac arrest is the major reason for its acceptance in halal poultry meat production. Apart from preserving the spiritual quality, the unconsciousness and insensibility resulted from a properly conducted electrical stunning procedure will also improve the eating quality without compromising the ethical quality traits particularly the welfare of the birds.

One must note that the stunning system may incur additional stress and compromise halal status if inefficiently executed due to shackling and the slaughtering process itself. Thus, proper guidelines on the combination of current, voltage, and frequency must be established and implemented to assure adherence to the halal regulation. Meanwhile, the existing halal regulations and standards on stunning electrical procedures require continuous improvement through scientific studies without compromising the welfare and meat-eating quality. Nonetheless, to ensure the effectiveness of stunning, the system shall always be monitored and regulated by trained in-house personnel. This review has listed the relationship and impacts of a well-executed and inefficient electrical water bath stunning system on poultry meat's spiritual, ethical, and eating quality.

DISCLOSURES

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in the present study.

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