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Identifying reasons for stun failures in slaughterhouses for cattle and pigs: a field study

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Abstract

Checking the effectiveness of stunning was one of the major tasks when the authors evaluated the stunning process on request of the slaughterhouse managements, retailers or competent authorities in slaughterhouses in Austria, Germany and Switzerland between the years 2000 and 2011. A total of 50 assessments in slaughterhouses for cattle and 116 for pigs were included in this study. For every assessment the technical features of the stunning device, the performance by the personnel and the clinical signs of the animals after stunning were recorded. The assessments of captive-bolt (CB) stunning were made in 1,823 cattle. For pigs, 63 assessments were carried out in electrical stunning (26 in a pen [ESP], 24 in a trap [EST] and 13 in an automatic restrainer [ESR]) and 53 assessments in CO_2 stunning, covering a total of 35,220 pigs (6,855 electrically stunned and 28,365 stunned using CO_2). The proportions of assessments in which there were no failures were 28% (CB), 12% (ESP), 21% (EST), 31% (ESR) and 13% (CO_2). The mean percentages of animals showing signs not compatible with sufficient depth of stunning were 13.5 (± 19.0)% (CB), 12.5 (± 16.4)% (ESP), 10.9 (± 11.4)% (EST), 3.2 (± 3.3)% (ESR) and 7.5 (± 13.0)% (CO_2) showing a high variability between premises assessed. Stunning effectiveness for cattle was better where a chest stick was performed compared to a neck cut. For pigs, less stunning failures occurred in electrical stunning where the two-cycle method (head/heart current) was applied compared to head-only stunning, and most of the failures in CO_2 stunning were due to insufficient dwell time. Reasons for the stunning failures are described and recommendations given to improve the situation.

Keywords: *animal welfare, captive-bolt stunning, cattle, CO_2 stunning, electrical stunning, pigs*

Introduction

Stunning of slaughter animals is a difficult issue: healthy animals must be rendered unconscious and killed in a short time to be further processed to become a product suitable for human consumption. Animal welfare, worker safety, product quality and economical aspects all have to be taken into account.

The aim of this study was to compile the findings of slaughterhouse inspections with a focus on the stunning process (captive-bolt stunning in cattle, CO_2 and electrical stunning in pigs) to give an impression on stunning effectiveness under field conditions and identify apparent reasons for stun failures.

The assessments were carried out on request of the slaughterhouse managements, retailers or the competent authorities. The results were analysed and we present recommendations about improvements for better stunning.

Materials and methods

Between 2000 and 2011, 116 assessments (pigs) and 50 assessments (cattle) were undertaken. These involved 58 pig-slaughter plants and 25 cattle-slaughter plants. The assessments were carried out during routine slaughter procedure in commercial plants in Germany, Austria and Switzerland. In some slaughterhouses, the assessments were repeated after one or two years and these have been counted as separate assessments as conditions had been changed. At every assessment, the technical properties of the stunning device, the performance of personnel and the clinical signs of the animals after stunning were recorded. The 50 assessments of captive-bolt stunning in cattle covered a total of 1,823 animals. Table 1 gives an overview of the assessments of pig plants using different electrical methods and CO_2 stunning.

The number of animals examined during each assessment varied according to slaughter speed and capacity of the slaughterhouse. Stunning effectiveness was checked over a period of at least 2 h.

In order to analyse the process, a definition of failures for each method was established according to scientific premises and experience of the authors. Each assessment was undertaken by two veterinarians except in small slaughterhouses with low slaughter speeds (eg 5–20 animals h^{-1}), where one veterinarian undertook the investigation. Electrical parameters and gas concentrations were assessed with the authors' own equipment and the results compared

Table 1 Assessments of pig stunning.

Method	Electrical stunning in a...			CO_2 stunning	Total
	Pen	Trap	Automatic restrainer		
Number of assessments	26	24	13	53	116
Number of pigs assessed for placement of electrodes and electrical contact	847	1,044	1,616	–	3,507
Number of pigs assessed for effectiveness before and after sticking	947	1,714	4,194	28, 365	35,220

Table 2 Criteria used in classifying the captive-bolt stunning of cattle.

Checkpoint	Criteria
Stunning pen	• Gun is misplaced according to recommended position or • Angle of gun to the skull is obviously differing from perpendicular or • Gun is malfunctioning (bad maintenance)
Before and after sticking (between stunning and sticking and until three minutes after sticking)	**OK**: immediate collapse, no attempts to get up, eye open and motionless, no breathing activity **Doubt**: eyeball is moving or showing abnormal movements (nystagmus, backwards rotation), breathing appears temporarily but less than four times **Not OK**: breathing lasts four times (or more) and/or spontaneous eyelid closure, corneal reflex positive and/or head with neck or front legs not relaxed/rolled up **Awake**: continuous regular breathing and tracking by the eye movements in vicinity, often together with attempts to straighten up or vocalisation

with those using the local equipment. Measurements of the parameters of electrical-stunning systems were done with an oscilloscope (Fluke scopemeter 196B, Fluke Deutschland GmbH, 79286 Glottertal, Germany) in combination with a current clamp (PR30, PB Messtechnik, 86161 Augsburg, Germany) and a resistance device (STM III Utzkohl, e-b-c Utz Kohl GmbH, 26121 Oldenburg, Germany) or adapters for the stunning devices creating a loop to use the current clamp during stunning. Gas-stunning systems were monitored with a CO_2-/O_2-Analyser (Checkmate 9900, Dansensor A/S 4100, Ringsted, Denmark) in combination with a pump (PM13421, KNF Neuberger GmbH, 79112 Freiburg, Germany).

Cattle

For cattle (including calves, cows, heifers, steers and bulls), the stunning process and its effectiveness were assessed at line speeds from 5 to 80 cattle per hour at two checkpoints: i) in the stun box (n = 1,407); and ii) before and after sticking (n = 1,823). Application of the gun and effect of the shot as well as the subsequent clinical signs were recorded. Captive-bolt guns were taken apart to check their maintenance.

Reference for the shooting position was the crossover point of two imaginary lines drawn between the base of the horns and the contralateral eye and certainly no further away than 2 cm radius from this point (Lambooij *et al* 1983; Ilgert 1985; Finnie 1993; EFSA 2004). According to the experience of the authors (von Holleben *et al* 2010) and Kaegi (1988), who referred to a point slightly more towards the top of the head (giving the outer corner of the eye as the lower reference point of the crossed lines), the optimum shooting position for heavy cattle (> 600 kg live-weight) was defined slightly higher. Failures of captive-bolt stunning of cattle were defined according to the criteria listed in Table 2.

In all our assessments animals categorised as 'Doubt' were followed on the line and checked whether they progressed to be 'OK', 'Not OK' or 'Awake'. The classification 'Not OK' was used, where animals were judged to be at risk of re-awakening completely.

Pigs electrical stunning

Electrical stunning of pigs was investigated in three different systems as outlined below:

(i) free moving pigs in a pen — some slaughter plants used head-only stunning but some used the two-cycle method by placing the electrodes first on the head and afterwards changing to an electrode position to allow an electric current to pass through the heart; (ii) pigs individually restrained in a trap/restraining box — here, again, distinction was made between head-only and the application of a two cycle head/heart current; and (iii) pigs restrained and stunned in automatic systems using high voltage (eg 600 V) or low-voltage, high-frequency systems as described by Lambooij *et al* (1997) and von Wenzlawowicz *et al* (1999).

In all the stunning systems examined, AC currents with sine or rectangular wave form were used. The frequency used for the head cycle varied from 50–1,330 Hz and for the heart cycle from 50–800 Hz. The criteria for failures in the electrical stunning of pigs are shown in Table 3.

When electrodes were placed such that the brain was not between the electrodes it was doubted that the

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Table 3 Criteria used in classifying the electrical stunning of pigs.

Checkpoint	Criteria
I Placement of electrodes and electrical contact	**OK**: electrodes span the brain for a minimum of 4 s and electrical contact (minimum current) is maintained for a minimum of 4 s*
	Not OK: both electrodes are placed rostral to the eyes or both electrodes are placed 5 cm or more behind the caudal edge of the ears or loss of contact (minimum current) before completion of the 4 s stun
II Electrical parameters	**OK**: minimum current is reached within 1 s and the current leads to an epileptic fit and heart fibrillation (in case of two-cycle method)
	Not OK: minimum current is not reached within 1 s, or the waveform/frequency is not adequate to induce an epileptic fit and heart fibrillation (in case of two-cycle method), or the current flow time is less than 4 s or is inadequate for stunning in automatic restrainers
III Effectiveness before and after sticking (between stunning and sticking and 30 to 60 s after sticking)	**OK**: epileptic activity, tonic + tonic-clonic phase, no breathing activity
	Doubt: no typical epileptic activity, gagging, single eyeball movements or eyelid closure
	Not OK: breathing persists for four cycles (or more) and/or there are spontaneous repeated eyelid closures or attempts to straighten up
	Awake: continuous regular breathing and tracking by the eye of movements in vicinity, often together with attempts to straighten up or vocalisation or flight reactions

* For stunning in an automatic restrainer the minimum current can be higher than 1.3 A and the necessary current flow time could be shorter than 4 s (eg 2.4 s head cycle [2.6 A], 1.6 s heart cycle [1.3A]).

Table 4 Features of the CO_2-stunning systems investigated.

Type	Number of investigations	Number of pigs examined	Number of pigs per gondola	Low stress (group entry)*	Slaughter speed of systems investigated (pigs per hour)
Butina Compact	3	150	1	No	100
Butina Combi	4	1,600	2	No	160–250
Butina Dip lift	8	530	4	No	80–150
Butina Combi Jumbo	10	6,940	3–4	No	310–585
Butina Backloader	19	16,557	4–8	Yes	180–860
Stork Sideloader	5	2,267	4	Yes	240–360
Banss Austria	4	321	4	Yes	180

* A 'low stress' CO_2 stunning system has a group entry, in which animals are driven into the system by automatic gates.

induction of the stunning process was painless and effective. A loss of contact was counted as a failure when it happened before the set minimum current flow time. A minimum current of 1.3 A applied for at least 4 s was required by law in the countries in which these investigations were carried out. For stunning in an automatic restrainer, minimum current was higher than 1.3 A and the current flow time shorter than 4 s. As it was not possible to follow every pig during the whole stunning process the number of animals checked at different checkpoints differs.

According to the state of the art for electrical stunning of pigs it is required that the applied current reaches a minimum value within 1 s in order to stun the animal before a painful electric shock can be sensed. Frequency and waveform were judged to be effective for stunning if alternating currents were used at a frequency between 50 Hz and 20 kHz (Anil & McKinstry 1992; Simmons 1995; Simmons & Daly 2007).

Pigs CO_2 stunning

Carbon dioxide (CO_2) stunning of pigs was investigated in various systems (see Table 4), all of which could be operated at different gas concentrations.

The stunning devices were operated in accordance with the regulations so that the pigs reached an atmosphere of more than 80% CO_2 in less than 30 s. The animals should then stay there sufficiently long (> 100 s). It was permissible for the stun-to-stick interval, which should be less than 20 s as a rule, to be prolonged under license for group stunning (eg up to 90 s for the seventh pig), but only if dwell time and CO_2 concentration were such as to guarantee effective stunning. Failures of CO_2 stunning were defined according to the criteria listed in Table 5.

As the effectiveness of CO_2 stunning of pigs is dependent on dwell time, CO_2 concentration, stun-to-stick-interval and bleeding quality, the following thresholds were used to categorise the stunning failures according to reasons (see Table 6).

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Table 5 Assessing the effectiveness of CO_2 stunning of pigs.

Classification	Clinical signs before and 30 s after sticking
OK	Eye open, non-reacting if touched, pupil wide open not sensible to light, muscles flaccid, mouth closed, no breathing activity
Doubt	Lid closes if eye is touched 1 or 2 times, pupil not wide open, 1–2 chest movements, mouth opening 1–3 times, single kicking when being shackled
Not OK	Breathing lasts for four cycles (or more) and/or there is spontaneous eyelid closure or attempts to straighten up
Awake	Continuous regular breathing and tracking by the eye of movements in vicinity, often together with attempts to straighten up or vocalisation or flight reactions

Table 6 Reasons for categorising stunning failures when using CO_2-stunning devices.

Stunning conditions	Reason for failure
Dwell time > 130 s and sticking is within 20–50 s*	Gas concentration is too low
CO_2 concentration > 85% and sticking is within 20–50 s*	Dwell time is too short
Dwell time > 130 s and CO_2 concentration > 85% + sticking is within 20–50 s*	Bleeding is ineffective (or late, when exceeding 50 s for the first pig)

* Average interval between leaving the stunning system and the start of bleeding of the first pig.

Table 7 Stunning effectiveness in cattle at different checkpoints (see Table 2).

Checkpoint (n)	Not OK (% of all animals)	Not OK (mean [± SD] % of animals per assessment)	Assessments with no failures
Stun box (n = 1,407)	8.0	7.6 (± 11.7)	19
Before/after sticking (n = 1,823)	9.2 including 1 awake	13.5 (± 19.0) including 2.1 (± 6.6) awake	17

Descriptive statistical analysis was performed using Microsoft Excel 2003.

Results and discussion

Cattle

In 14 out of 50 assessments, stunning was performed without failures (ie with correct shooting position and angle and resulting in sufficient depth of stunning). The average slaughter speed was 20 cattle h^{-1} (min 5 max 50).

Table 7 shows that, overall, 8% of the cattle received an inaccurate shot (ie either not perpendicular to the skull or outside the recommended shooting position) and the effectiveness of stunning was found to be insufficient in 9.2% of the cattle. However, there were huge differences between the assessments. The data are further presented in relation to the types of stunning pens used in Table 8 and in relation to stunning and bleeding conditions in Table 9.

Table 8 shows that the position and angle of the stunning device for adult cattle can be markedly improved when head movement is restricted (inaccurate shots averaged 35% without head restraint but only 4–10% where head restraint was used). However, this has to be considered in relation to slaughter speed also. This averaged 22 animals per hour for plants using a concave table for the head, 45 animals h^{-1} for plants where the pen was additionally equipped with a back pusher, and up to 55 animals h^{-1} where the head and neck were closely restrained by a mobile table and neck yoke. In practice, if plants exceed a certain slaughter speed, additional restraint equipment within the stunning pen is necessary and often installed to achieve a better shooting accuracy (von Holleben 2007). At plants with a slaughter speed of about 20 animals h^{-1}, perpendicular shooting angle was more regularly achieved than at higher slaughter speeds, probably because the operators had more time.

However, it is not possible to conclude that the head-fixation method significantly influenced the proportion of stunning failures because the systems differed in other ways also. For example, in the use of pneumatic as opposed to cartridge-fired stunners. So, the better results for stunning effectiveness cannot be attributed only to the method of head restraint. For calves, the proportion of overall stunning failures was zero for close-head fixation although shooting accuracy did not seem to improve, but in all these cases pneumatic stunning devices were also used. This indicates that shooting accuracy becomes less critical if high-powered devices are used (Gregory 2007). The same effect can be assumed for adult cattle. Using high-powered pneumatic guns, it is often more difficult to achieve optimum shooting position and angle but slight deviations do not affect stunning effectiveness.

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Table 8 Accuracy (position, angle) of captive-bolt stunning of cattle in relation to the types of restraint used.

Type of restraint (type of cattle)	Number of animals/ Number of assessments/ Slaughter speed (mean, min-max)	Position of stunning device Not OK (% of all animals, % of cattle per assessment (mean [± SD])	Number of assessments in which shooting angle was not regularly met
No head restraint (adult cattle)	138 animals 3 assessments 21 (10–40) cattle per hour	29.0 35.4 (± 10.7)	3 out of 3
Concave table for the head, no back pusher (adult cattle)	375 animals 20 assessments 22 (10–50) cattle per hour	4.3 4.6 (± 9.8)	7 out of 20
Concave table for the head and back pusher (adult cattle)	354 animals 11 assessments 45 (20–57) cattle per hour	8.2 9.9 (± 11.4)	10 out of 11
Close head fixation and back pusher (adult cattle)	338 animals 8 assessments 55 (42–73) cattle per hour	6.2 7.0 (± 4.2)	7 out of 8
No head restraint (calves)	138 animals 3 assessments 75 (65–80) cattle per hour	3.8 4.6 (± 6.3)	2 out of 3
Close head fixation and backpusher (calves)	50 animals 1 assessment 65 cattle per hour	4.0 4.0	1 out of 1

Table 9 Effectiveness of captive-bolt stunning as measured before and after sticking and in relation to stunning and bleeding conditions.

Conditions	Not OK (% of animals)	Not OK (mean [± SD]% of animals per assessment)	Number of assessments with no failures before or after sticking
Slaughter speed ≤ 30 cattle per h (n = 510, 26 assessments)	15.7 including 1.4 awake	19.6 (± 23.2) including 3.2 (± 8.6) awake	11 out of 26
Slaughter speed > 30 cattle per h (n = 1,313, 24 assessments)	6.7 including 0.8 awake	6.7 (± 9.7) including 0.8 (± 3.5) awake	6 out of 24
Neck cut (n = 689, 32 assessments)	13.6 including 1.3 awake	17.6 (± 21.5) including 2.8 (± 7.8) awake	12 out of 32
Chest stick (n = 1,134, 18 assessments)	6.5 including 0.8 awake	6.2 (± 10.3) including 1.3 (± 4.0) awake	5 out of 18
Mean stun to stick time > 60 s (n = 965, 27 assessments)	10.3 including 0.5 awake	16.8 (± 20.6) including 2.0 (± 4.6) awake	7 out of 27
Mean stun to stick time ≤ 60 s (n = 858, 23 assessments)	8.0 including 1.5 awake	9.6 (± 16.4) including 2.6 (± 8.6) awake	10 out of 23
Neck cut and mean stun to stick time > 60 s (n = 441, 19 assessments)	15.6 including 1.1 awake	21.6 (± 22.9) including 2.4 (± 5.0) awake	6 out of 19
Neck cut and mean stun to stick time ≤ 60 s (n = 248, 13 assessments)	10.1 including 1.6 awake	11.8 (± 18.4) including 3.5 (± 11.0) awake	6 out of 13
Chest stick and mean stun to stick time > 60 s (n = 524, 8 assessments)	5.7 but 0.0 awake	5.5 (± 4.1) including 0.0 (± 0.0) awake	1 out of 8
Chest stick and mean stun to stick time ≤ 60 s (n = 610, 10 assessments)	7.2 including 1.5 awake	6.7 (± 13.7) including 1.5 (± 4.2) awake	4 out of 10

Table 10 The effectiveness of electrical stunning of pigs at different checkpoints (see Table 3).

Checkpoint	Number of animals/ Number of assessments/ Slaughter speed (mean, min–max)	Not OK (% of all animals)	Not OK (mean [± SD] % of animals per assessment)	Number of assessments with no failures
Electrical stunning in a pen				
Placement of electrodes and electrical contact	847 pigs 26 assessments 62 (6–200) pigs per h	25.6	28.3 (± 21.5)	3 out of 26
Effectiveness: Total	947 pigs 26 assessments 62 (6–200) pigs per h	11.4 including 2.1 awake	12.5 (± 16.4) including 2.3 (± 4.9) awake	3 out of 26
Effectiveness: Two cycle method head/heart current	621 pigs 16 assessments 64 (30–180) pigs per h	9.5 including 1.5 awake	10.5 (± 16.6) including 1.1 (± 3.1) awake	4 out of 16
Effectiveness: Head-only stunning	326 pigs 10 assessments 59 (10–200) pigs per h	15.0 including 3.4 awake	15.7 (± 16.3) including 4.1 (± 6.6) awake	3 out of 10
Electrical stunning in a trap				
Placement of electrodes and electrical contact	1,074 pigs 24 assessments 143 (50–230) pigs per h	7.4	9.3 (± 11.9)	7 out of 24
Effectiveness: Total	1,714 pigs 24 assessments 143 (50–230) pigs per h	11.1 including 3.9 awake	10.9 (± 11.4) including 4.3 (± 6.7) awake	5 out of 24
Effectiveness: Two cycle method head/heart current	430 pigs 5 assessments 198 (180–230) pigs per h	6.3 including 3.8 awake	4.9 (± 6.3) including 3.0 (± 4.0) awake	1 out of 5
Effectiveness: Head-only stunning	1,284 pigs 19 assessments 128 (50–200) pigs per h	12.7 including 3.9 awake	12.5 (± 12.0) including 4.6 (± 7.3) awake	4 out of 19
Electrical stunning in an automatic restrainer				
Placement of head electrodes	1,616 pigs 13 assessments 392 (100–520) pigs per h	7.3	8.3 (± 4.7)	1 out of 13
Placement of heart electrode	1,131 pigs 11 assessments 416 (180–520) pigs per h	3.7	6.3 (± 10.3)	3 out of 11
Effectiveness: Total*	4,194 pigs 13 assessments 392 (100–520) pigs per h	3.3 including 1.9 awake	3.2 (± 3.3) including 1.1 (± 2.2) awake	4 out of 13

* In all automatic restrainers the current passed through the heart.

In Table 9, we present the results of the effectiveness of stunning in relation to stunning and bleeding conditions. These results for overall stunning effectiveness and the reasons for failures (see Tables 7 and 9) were comparable with those of other studies (Grandin 2003; Endres 2005; Gregory *et al* 2007; Atkinson & Algers 2009; Gouveia *et al* 2009). In our study, stunning effectiveness at a lower slaughter speed (< 30 cattle h^{-1}) was lower than in plants with higher slaughter speeds. The slower-speed plants restrained the head insufficiently and performed late sticking and a neck cut. Stunning effectiveness was generally better where a chest stick was performed (compared to a neck cut). A stun-to-stick-interval of less than 60 s was more important where a neck cut was performed than where bleeding was by chest stick. This is in line with the findings of Gregory *et al* (1988) that a chest stick leads to greater blood loss in relation to bodyweight within 60 s and emphasises the fact that stunning effectiveness, as judged after sticking, is a result of stunning as well as bleeding quality. In conclusion, a well-performed chest

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Table 11 The effectiveness of two-cycle electrical stunning of pigs in a pen in relation to the frequency of the current applied across the heart.

Number of assessment	50 Hertz (n = 180)			80 Hertz (n = 198)			100 (200) Hertz (n = 183)		
	Current**	Failures (%)	SS int	Current**	Failures (%)	SS int	Current**	Failures (%)	SS int
1	1.6 A	0	12 s	2.2 A	67	17 s	1.3 A	14	19 s
2	1.8 A	0	69 s	2.2 A	20	14 s	1.3 A	10	12 s
3	2.1 A	4	18 s	1.8 A	17	18 s	1.2 A	0	12 s
4	2.1 A	0	8 s	2.0 A	0	13 s	1.3 A*	13	26 s
5	2.0 A	0	8 s	2.0 A	8	13 s	1.9 A	14	13 s
Mean (± SD)		0.8 (± 1.8)			22.4 (± 26.0)			10.3 (± 6.0)	

SS int: Stun-stick interval.
* Assessment with 200 Hz.
** Current applied to the head.

stick may prevent cattle from reawakening in situations where stunning conditions are sub-optimal. Stunning effectiveness in relation to the type of stunning devices could not be analysed in detail as other factors, such as sticking quality and shooting accuracy, could have confounded the results. Nevertheless, it might be an important side observation during the assessments that heavy stunning apparatus or guns with a round top surface may increase the risk of shooting inaccurately or not perpendicular to the skull surface and that special problems in practice occurred with very heavy cattle (> 600 kg live-weight), for which some cartridge-driven devices totally filled with recuperating sleeves that were satisfactory for smaller animals did not seem to be adequate.

Pigs electrical stunning

The results of monitoring the electrical stunning of pigs are presented according to the different methods used: pen, trap and automatic systems. For stunning in a pen, all pigs were bled after being shackled and hoisted. The average stun-to-stick-interval was 15 s. In three out of 26 assessments, the placement of the electrodes in the pen as well as stunning effectiveness were satisfactory (no failures). For stunning in the trap, all pigs were bled in a recumbent position within 5 to 9 s after leaving the trap. In five out of 24 assessments, there were no failures concerning the placement of the electrodes and effectiveness were satisfactory at the same time.

For stunning in an automatic chest-belt restrainer, pigs were bled in a recumbent position with an average stun-to-stick-interval less than 10 s. In only one of the assessments there were no failures concerning the placement of the electrodes, but four of the 13 assessments delivered an excellent stunning effectiveness.

With regard to current application, Table 10 shows that fixation in a trap or an automatic restrainer compared to group stunning in a pen resulted in markedly fewer failures due to wrong electrode placement or bad electrical contact but, in the end, technical solutions alone did not solve the problem. Even for automatic systems, electrode placement included 8% failures on average, although overall stunning effectiveness in the series we have examined was highest in automatic systems. This was due to higher head currents (eg setting 2.6 A, see below), used in automatic systems to achieve effective stunning even if electrode position was slightly incorrect. Of course, any deviation from the proper electrode position should be avoided because otherwise insufficient current will pass the brain.

Failures in electrode placement and electrical contact are more likely to occur if pigs are excited by bad handling, especially if the slaughter speed is too high in relation to the system used. With automatic restrainers, careful maintenance is needed for the photo-sensors and selection of the appropriate size and weight of the pigs is crucial. Better application of electrodes can be achieved if pre-slaughter handling avoids excitement. The number of pigs in a pen should not exceed two to four animals. In all handling systems, ethological aspects should be considered, aimed at moving pigs by attracting them rather than by driving them. As some time is necessary for the animals to move and to calm down, the maximum possible slaughter speed of the handling and stunning system has to be defined (see von Holleben 2007).

In this study, we found that use of incorrect current parameters led to between 3 and 25% failures per assessment. One reason was the current applied to the head was too low and the application time too short (eg 1.3 A for 2 s). This sometimes occurred with improper placement of the electrodes, where the settings for minimum time and current were set to those appropriate only if the placement of the electrodes was precisely correct. In studies undertaken by Lambooij *et al* (1997) and von Wenzlawowicz *et al* (1999) of an automatic system, a minimum current of 2.6 A at 800 Hz for 2.6 s for the head cycle and 1.3 A at 50 Hz for 1.6 s for the heart cycle (both AC sine wave) were used to achieve effective stunning, taking into account that inaccurate placement in automatic systems has to be compensated by a higher minimum current.

For the heart part of the cycle, incorrect current parameters observed included insufficient currents (eg < 1.0 A) and/or too high frequencies (> 50 Hz). Frequencies of 100 or 80 Hz were found to be less effective than 50 Hz (see Table 11). This applied for stunning devices using a constant frequency

Table 12 The effectiveness of CO_2 stunning.

Effectiveness	Number of animals/ Number of assessments/ Slaughter speed (mean, min-max)	Not OK (% of all animals)	Not OK (mean [± SD] % of animals per assessment)	Number of assessments with no failures/ Number of assessments with failure rates of > 0 to 0.5%
Effectiveness total	28,365 pigs 53 assessments 355 (80–860) pigs per h	1.8 including 0.6 awake	7.5 (± 12.96) including 2.8 (± 5.82) awake	7 out of 53/ 12 out of 53
Failures due to gas concentration too low (≤ 85%)	4,741 pigs 8 assessments 318 (180–488) pigs per h	2.3 including 0.6 awake	3.2 (± 3.63) including 0.7 (± 1.04) awake	0 out of 8/ 0 out of 8
Failures due to dwell time too short (≤ 130 s)	6,044 pigs 21 assessments 240 (80–585) pigs per h	5.5 including 2.0 awake	15.4 (± 16.88) including 6.8 (± 7.78) awake	0 out of 21/ 0 out of 21
Failures due to ineffective sticking*	3,356 pigs 11 assessments 294 (100–630) pigs per h	2.8 including 0.4 awake	6.9 (± 7.84) including 1.3 (± 2.95) awake	0 out of 11/ 0 out of 11

* In one plant sticking was performed very late (on average 77 s after being expelled from the chamber, in all the other plants the failures were allocated to sticking quality).

for the heart cycle as well as for those where frequency decreased from 400–500 Hz to 100, 80 or 50 Hz within the first seconds. An effective application of the heart cycle helps when stun-to-stick interval is long (eg in a pen) or ineffective (eg in a trap or restrainer). Selecting the wrong frequency or current or incorrect placement of the heart electrode (on the front-leg or shoulder) resulted in a higher proportion of pigs regaining consciousness in all systems.

In practice, current is often reduced for carcase quality reasons and is not based on sound science regarding that required for proper stunning. Such use of inadequate currents clearly demonstrates the need for manufacturers to provide clear instructions about the recommended combination of parameters for their equipment.

According to current science and our findings we recommend the following:

• Alternating currents with frequencies between 50 and 800 Hz should be used with sufficient current and current application time adapted to take account of the precision of electrode placement. In addition, either an effective heart cycle (two-cycle method) has to be applied or effective bleeding must be performed within less than 10 s after the end of current flow.

• Head cycle — the minimum AC current for the head cycle has to be 1.3 A at 50 to 800 Hz for at least 4 s. For heavier pigs (exceeding 150 kg live-weight) current must be between 1.8 and 2.0 A (von Wenzlawowicz 2009). Automatic systems require higher minimum currents, possibly combined with shorter application time.

• Heart cycle — in all systems the minimum current for the heart cycle should be 0.8 A AC for at least 4 s. Automatic systems may require higher minimum currents, possibly combined with shorter application time. The heart current should include a period with a frequency of 50 Hz.

Late sticking (eg > 15 s after end of current flow) or ineffective sticking (small wound, small amount of blood flow) and no monitoring of stunning effectiveness during bleeding (and no back-up stunning) were the causes for mean failure rates of between 12 and 16% of the pigs stunned in a pen or trap (see Table 10). A frequent mistake in practice is that slaughter staff do not monitor the pigs after sticking, because they think that sticking will result quickly in death and that re-awakening after sticking is hardly possible. Even in slaughterhouses where pigs were stuck during the application of the current in a trap, recovery from the stun could not be excluded. Recovery in spite of very early sticking (during application of the current), could be due either to the fact that the epileptic fit might not fully develop because of the early blood loss or because of reduced bleeding efficiency during strong tonic muscle cramps. Head-only stunning followed by sticking was more likely to produce failures than the two-cycle method (see Table 10). With head-only stunning, an acceptable effectiveness was only achieved using long-current application times, eg 8–18 s, and a stun-to-stick-interval of less than 10 s. The importance of effective sticking after head-only electrical stunning has been clearly demonstrated by Anil *et al* (2000). A short stun-to-stick-interval is beneficial in any case to prevent pigs from recovering as well as improving meat and carcase quality (Meiler 2006). This applies to all three methods. In special cases where a long stun-to-stick-interval cannot be avoided parameters for a 'safe' heart cycle must be used (1.3 A, 50 Hz, 4 s).

CO_2 stunning of pigs

In seven out of 53 assessments an excellent stunning effectiveness (0% failures) was achieved and 12 resulted in less than 0.5% of failures. The mean average stun-to-stick-intervals across all 53 assessments were 32 s for the first pig,

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39 s for the second, 50 s for the third, 59 s for the fourth, 67 s for the fifth and 76 s for the sixth pig. But these periods varied between devices and according to the staff available, eg the seventh pig could be bled within 66 s after being expelled from the chamber. In only one plant, the animals were stuck whilst in a recumbent position 5 to 6 s after leaving the chamber. The results for the effectiveness of CO_2 stunning are shown in Table 12.

Overall, CO_2 stunning was highly effective. Of all pigs assessed after CO_2 stunning, 1.8% showed signs not compatible with sufficient depth of stunning. However, the average failure rate of assessments was 7.5%. This is because there were great differences in stunning effectiveness between plants. Taking into account that the slaughter speed can be very high in modern pig gas-stunning systems, a relatively low percentage of stunning failures may nevertheless indicate compromised welfare of a large number of pigs. The main reason for failures in CO_2 stunning is insufficient dwell times as previously stated by von Holleben *et al* (2002). This often happens when slaughter speed is too high. Therefore, it is necessary that maximum slaughter speed is clearly described by the manufacturers according to the number and size of gondolas and other factors like depth of the pit or stun-to-stick interval, and that it is carefully checked by the competent authorities. Minimum space requirements during CO_2 stunning should never go below those prescribed in the transport legislation. Gas concentration may be too low or inadequately maintained, due to ventilation issues, insufficient depth of the pit, lack of heating the gas in winter, defective or incorrectly positioned sensors, incorrect settings or inadequate gas control or supply pressure. Even after very long dwell times in high CO_2 concentrations, some pigs may still wake up during bleeding, which emphasises the importance of having an effective back-up procedure. Late or ineffective bleeding is often due to lack of manpower or skill. Technical solutions for monitoring bleeding quality are under development, but thresholds have only been verified for a small range of conditions so far and are largely dependent on the weight of the pigs (Troeger *et al* 2005). Therefore, some doubt remains at present as to whether these systems will securely preclude the possibility of conscious animals proceeding to scalding.

Animal welfare implications and conclusion

Overall stunning effectiveness, as revealed by the assessments reviewed here, is far from optimal but a few points have to be mentioned to integrate the results. Firstly, although we covered a wide range of slaughter conditions and a huge number of animals, our study is not necessarily representative. It simply reveals the picture that we have seen over the last ten years from plants visited at the request of the slaughterhouse managements, retailers or competent authorities. It is hoped that things have changed as a result of our work and advice. Secondly, for all stunning systems observed, some plants achieved optimum stunning effectiveness but others had a high failure rate. In fact, the most striking result is the high variability between the assessments. Thus, it is very important to focus on how to maximise stunning effectiveness. Achieving good stunning effectiveness in practice is a fundamental challenge as a number of factors are involved, including those relating to technology (system, settings, maintenance), the knowledge and skills of the staff and the conditions of the animals (von Wenzlawowicz 2006). The best slaughter companies were those that had chosen a stunning system matching the specific demands of the plant, and in which management put special emphasis on animal welfare at stunning. With regards to monitoring and continuously improving stunning effectiveness, in these companies there was excellent co-operation between the implementing staff, plant technicians, animal welfare officers, veterinarians and where necessary external experts (von Holleben 2009). Manufacturers of stunning equipment have a special responsibility, to give guidance how to operate their systems and to specify maximum possible slaughter speed and key parameters for all settings. Independent licensing of methods and systems would provide greater securities, but would be no substitute for individual licensing and inspection on site.

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