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Review Article

A scientific comment on the welfare of domesticated ruminants slaughtered without stunning

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Abstract

This review provides a scientific comment on the welfare of ruminants slaughtered by ventral-neck incision without stunning. Evidence is derived from studies of calves, sheep and goats. Reference is also made to findings in other mammals including humans.

Pain is an inherently subjective experience and only indirect indices are available in animals. Neurophysiological tools are widely used in humans to assess pain and have demonstrated that electroencephalographic (EEG) variables correlate well with subjective evaluations of pain. These neurophysiological tools have also been applied in animal studies.

In humans pain is associated with major cutting injuries and it is widely accepted that farm animals also experience pain due to such injuries. Overwhelming international scientific opinion has long been that slaughter by neck incision of conscious animals causes pain. A series of studies in calves demonstrated that slaughter by ventral-neck incision is likely to be perceived as painful. It is proposed that, as in cattle, non-stunned sheep and goats would experience pain in a similar manner.

The precise assessment of the point after slaughter at which non-stunned animals become insensible remains a major methodological challenge. In sheep it is at least 2–8 seconds, but may be 8–20 seconds in duration. In cattle the mean duration is similar, but can commonly be extended to longer than 60 seconds with occasional instances of even greater durations.

Taken together, these findings indicate that because the slaughter of cattle, sheep and goats by ventral-neck incision without prior stunning is likely to cause pain, this poses a risk to animal welfare.

KEY WORDS: *Slaughter, ruminant, stunning, animal welfare*

Introduction

Human beings overwhelmingly report pain associated with major cutting injuries to tissues and it is widely accepted in science that farm animals and other mammals also experience pain due to such injuries (Gregory 2004; Mellor *et al.* 2008, 2009). Furthermore, the consensus of international scientific opinion has long been that slaughter by neck incision of conscious animals would very likely cause pain (Anonymous 2004; Gregory *et al.* 2010; Nakyinsige *et al.* 2013). Studies in calves at Massey University demonstrated that the act of slaughter by ventral-neck incision would indeed be painful in the period between the incision and the onset of insensibility (Gibson *et al.* 2009a,b,c; Mellor *et al.* 2009). In view of the widely acknowledged similarity between cattle, sheep and goats with respect to the functional anatomy of the neck, the physiology of peripheral nerves, the brain centres associated with the experience of pain and the control of acute pain (Anonymous 2004; Gregory *et al.* 2010; Nakyinsige *et al.* 2013), it is proposed that, as in cattle, non-stunned sheep and goats would experience pain during the period between the neck incision and the onset of insensibility after slaughter. This raises an important question for all three species: How long does it take after the neck incision for insensibility to supervene? Subsidiary questions include: How may pain be assessed during and after the neck incision? What parameters are available to demonstrate the onset of insensibility? And, what factors may contribute to between-species differences in the interval between the neck incision and insensibility?

This review therefore focuses on the welfare of cattle, sheep and goats at the point of slaughter. Supporting scientific evidence is derived from specific studies of ruminant livestock. Where appropriate, reference is also made to findings in other mammals. Reference to non-mammalian vertebrates has been specifically excluded. For general knowledge about the direct experience of pain, reference is made to human studies and clinical practice. Whilst definitive answers to significant questions addressed are not yet available, this review attempts to provide an account of the current state of knowledge in this area.

Pain in relation to slaughter by neck incision

Pain has been defined as an unpleasant sensory and emotional experience associated with actual or potential tissue damage or

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EEG Electroencephalographic/electroencephalogram described in terms of such damage (Merskey 1979). Noxious stimuli act on a variety of physiological sensors, known as nociceptors, and these generate electrical impulses in their associated nerves that, in their turn, convey these impulses to the higher centres of the central nervous system where they are interpreted as pain (Merskey 1979). Processing of nociceptive impulses by the brain gives rise to the complex emotional and experiential components of pain. Pain is an inherently subjective phenomenon that is due as much to the state of the nervous system that perceives it as it is to the stimuli that are perceived (Casey 1999). Pain mechanisms warn animals against situations that may cause damage to their tissues and give them the opportunity to learn to avoid such harmful situations in future. In addition, and importantly, pain is inherently unpleasant and as such is considered to be a negative influence on the welfare of sentient animals (Gregory 2004; Phillips 2007; Mellor *et al.* 2008).

The act of slaughter usually involves severing major blood vessels in order to kill the animal by exsanguination. This inevitably involves extensive incision through additional sensitive tissues in the neck and/or thorax leading to stimulation of nociceptors in these tissues. This may lead to the perception of pain by the animal before unconsciousness and death supervene.

Pain and its assessment

While humans can describe their pain, this is not possible for other species and so only indirect indices of pain are available for use in animals. A number of physiological and behavioural indices have been used in studies of animal pain (Mellor *et al.* 2008, 2009). A selection of these indices is summarised in Table 1. Some of these indices have been found to be very valuable, but many also reflect impacts of non-painful stressors and, as such, caution must be exercised when interpreting changes in these indices (Mellor *et al.* 2000; Gregory 2004). Studies of potentially painful stimuli that utilise such indices must be carefully designed in order to prevent the animals from being exposed simultaneously to non-painful events that might also influence the indices being used (Lester *et al.* 1996; Gregory 2004, Mellor *et al.* 2008). Despite these limitations some of these less specific indices have proved to be useful in closely controlled experimental circumstances (Mellor *et al.* 2000). However, a sufficient level of control is extremely difficult to achieve in studies of complex manipulations where there may be changes in indices due to interactions between different stimulatory mechanisms. Studies of slaughter fall into this category because of complex interactions between factors that include noxious stimulation due to neck incision, loss of brain perfusion leading to cerebral hypoxia/anoxia and the inevitable onset of unconsciousness and the eventual death of the animal (Johnson *et al.* 2012).

Neurophysiological tools are now widely used in humans to assess pain in both research and clinical settings (Apkarian *et al.* 2005). These tools have also been applied to other mammals in seeking better ways to monitor the adequacy of anaesthesia, as well as to assess the efficacy of various analgesic agents (Murrell and Johnson 2006). The value of neurophysiological tools in assessing pain and its alleviation in farm animals has also been demonstrated (Johnson *et al.* 2005b, 2009; Gibson *et al.* 2007). Overall, the use of variables derived from electroencephalograms (EEG) as indices of pain has now been validated in eight mammalian species (Johnson *et al.* 2012).

Slaughter by neck incision and pain assessment

As noted above, human beings overwhelmingly report pain associated with major cutting injuries to tissues (Gregory 2004), and it is widely accepted that farm animals and other mammals also experience pain due to such injuries (Gregory 2004; Mellor *et al.* 2008). The physiological basis for this assumption as it relates generally to any extensive incision is, first, that such an incision transects skin, muscle, arteries, veins, sensory nerves (including nociceptive nerves), other nerves and connective tissue. Second, that these soft tissues are sensitive to noxious stimuli (Loeser *et al.* 2001; Gregory 2004). Third, that transecting most of these tissues and the nerves themselves will cause a barrage of impulses to travel to the brain leading to the experience of acute pain (Gregory 2004). Fourth, that inflammatory reactions instigated by products of cell damage lead to the production of eicosanoids that activate pain pathways in the period following tissue damage (Gregory 2004). Allied to these observations, imaging and electrophysiological studies in humans indicate that specific areas of the brain including the primary somatosensory cortex, cingulate gyrus, insula cortex and pre-frontal cortices are activated during the experience of acute pain (Gregory 2004; Apkarian *et al.* 2005). In lightly anaesthetised mammalian farm animals, activity in these pathways can be manipulated using a variety of pharmacological approaches, including nerve blockade and administration of analgesics, that also reduce behavioural and physiological indicators of pain in conscious animals (Gibson *et al.* 2007; Mellor *et al.* 2008; Johnson *et al.* 2012).

The above evidence all points to the capacity for mammals to perceive pain in a very similar way to humans and accordingly the overwhelming international scientific opinion has long been that slaughter by neck incision of conscious animals would cause significant pain before the onset of insensibility (Anonymous 2001, 2003, 2004).

The physiological basis of this assumption specifically in relation to slaughter by neck incision was outlined by Gregory (2004). Firstly, the neck incision is very extensive, transecting skin, muscle, trachea, oesophagus, carotid arteries, jugular veins, other blood vessels, sensory nerves (including nociceptive nerves), other nerves and connective tissue. These soft tissues are all sensitive to pain. Secondly, transecting the tissues and the nerves of the neck will cause a barrage of impulses to travel to the brain leading to the experience of acute pain. Thirdly, nerve conduction velocities ensure that activation of brain centres following major cutting injury occurs within milliseconds. Therefore, the potential experience of pain is directly relevant to the events following the neck incision but prior to the onset of insensibility. Fourthly, stunning abolishes consciousness and, therefore, perception of any pain that occurs. Effective methods currently include percussive and electrical stunning (Gregory 1998). Fifthly, the inflammatory reactions that would be associated with the tissue damage occur over a longer time course than is relevant to the events following slaughter (Woolf and Chong 1993).

Nevertheless, few if any direct studies of pain following slaughter by neck incision were undertaken prior to the work of Gibson *et al.* (2009a,b,c,d). This is primarily because most of the indices previously available were not suitable for this purpose for a number of reasons including: they may not be specific to pain in the context of a complex manipulation such as slaughter, e.g. heart rate, hormone responses, behaviour; the time course may be too short for a meaningful response to be expressed, e.g. hormone responses, behavioural aversion; and features in the

Table 1. Some physiological and behavioural indices of distress responses to noxious stimuli in ruminants and other species. From Mellor *et al.* (2000, 2008) and Gregory (2004).

Physiological indices	Behavioural indices
Concentrations of hormone in blood	Vocalisation
Adrenaline, noradrenaline	Whimpers, howls, growls, screams, grunts, moans, squeaks, squeals, chirps, silent
Corticotrophin releasing factor, adrenocorticotrophic hormone, glucocorticoids. (e.g. cortisol)	
Prolactin	Posture
	Cowers, crouches, huddled, hiding, lying (legs extended or some legs tucked in), standing (on all or not all legs, rigid, head against wall, drooping)
Concentrations of metabolites in blood	
Glucose, lactic acid, free fatty acids, β-hydroxybutyrate	
	Locomotion
Other variables	Reluctant to move, awkward, shuffles, staggers, falls, stands up, lies down repeatedly, circles, escape/avoidance movements, pacing, restless, writhing
Heart rate, breathing (rate and depth), packed cell volume, sweat production, muscle tremor	
Body temperature	Demeanour
Concentrations of α-acid glycoprotein in plasma, blood leukocyte counts, cellular immune responses, humoral immune responses	Withdrawn, depressed, quiet, docile, miserable, agitated, anxious, frightened, terrified, aggressive

process of slaughter may inherently confound the measure e.g. heart rate, blood pressure, or may prevent its expression, e.g. vocalisation, physical withdrawal responses. Accordingly, the focus of most studies has been on determining the period of sensibility that followed the neck incision in the belief that pain would probably occur until the onset of insensibility (Newhook and Blackmore 1982; Gregory and Wotton 1984; Devine *et al.* 1986). These studies will be considered in more detail below.

It should be recognised that although the majority scientific view was that the neck incision would cause pain, an alternative view has been held by others who claimed that significant pain may be avoided with the use of an extremely sharp knife and a swift, clean incision followed by a free bleed-out (Grandin 1994; Levinger 1995; Rosen 2004).

Evidence on pain and the neck incision

Non-slaughter research

Electroencephalographic studies, which involved use of a new minimal anaesthesia model (Murrell and Johnson 2006), have provided more persuasive neurophysiological evidence for perception of pain by animals.

The principal rationale for this approach, outlined by Johnson (2008), is that the EEG gives a direct indication of the activity of the cerebral cortex (Silva 2004). Functional imaging techniques have demonstrated that certain cortical structures, in particular the anterior cingulate gyrus, play a central role in pain perception (Apkarian *et al.* 2005). Studies in human volunteers and in patients experiencing pain have demonstrated that in contrast to the more classical physiological measures, EEG variables correlate well with subjective evaluations of pain (Chen *et al.* 1989, Hunter *et al.* 2009; Graversen *et al.* 2012). These findings demonstrate the value of quantitative EEG analysis as an indicator of the degree of pain perceived by an animal, as opposed to the magnitude of the noxious stimulus applied to the animal.

Quantitative EEG analysis has now been used as an indicator of the experience of pain in humans, horses, sheep, pigs, rats, red deer, wallabies, cattle and dogs (Chen *et al.* 1989; Murrell *et al.* 2003; Diesch *et al.* 2005; Johnson *et al.* 2005a,b; Haga and Ranheim 2005; Murrell and Johnson 2006; Gibson *et al.* 2007). The animals in these studies were lightly anaesthetised such that they were not able to experience pain, but their cerebral cortices responded in a similar manner to those of conscious animals subjected to noxious stimulation (Ong *et al.* 1997). Although anaesthesia blunts EEG responses, researchers have developed a technique of minimal anaesthesia that preserves the EEG responses sufficiently for them to remain a meaningful measure of the pain that an animal would perceive were it conscious (Murrell and Johnson 2006).

Calf slaughter studies

In a series of studies in calves, the potential for slaughter by ventral-neck incision to be perceived as painful, in the interval between the incision and subsequent loss of sensibility, was investigated. The impact of ventral-neck incision was reported in the first paper (Gibson *et al.* 2009a). The neck incision was associated with significant noxious sensory input that would have been likely to be perceived as pain in conscious animals. The question of whether this noxious sensory input was due primarily to the transection of neck tissues or to interruption of blood flow to and from the brain was addressed in the second paper (Gibson *et al.* 2009b) which demonstrated that the predominant noxious stimulus was transection of the sensitive neck tissues rather than the interruption of cerebral perfusion. The third paper reported the impact of non-penetrative captive-bolt stunning on the features of the EEG, which were assessed quantitatively for the first time (Gibson *et al.* 2009c) and indicated that the vast majority of animals were rendered insensible before data were able to be collected from about 3 seconds after stunning. The fourth paper assessed the extent to which applying a non-penetrative captive bolt stun 5 seconds after ventral-neck incision ameliorated the noxious sensory input caused by the incision (Gibson *et al.* 2009d). This paper showed that the stun prevented the subsequent development of responses in the EEG to noxious sensory input in most of the animals. These studies, together with the work leading to the development of the minimal anaesthesia model, have recently been reviewed in more detail (Johnson *et al.* 2012).

This information demonstrated clearly for the first time that the act of slaughter by ventral-neck incision is likely to be perceived as painful in the period between the incision and the onset of insensibility. The effects of captive-bolt stunning in producing rapid insensibility and ameliorating changes in the EEG associated with neck incision have also been clearly demonstrated. Taken together, these papers provide the most comprehensive electrophysiological picture to date of the events surrounding slaughter by neck incision, and provide further support for the value of stunning in preventing pain in animals subjected to this procedure.

Relevance to slaughter of sheep and goats

In view of the lack of difference between cattle, sheep and goats with respect to salient features of the functional anatomy of the neck, neurophysiology of peripheral nerves, relevant brain centres, pain experience and control of acute pain, it is anticipated that sheep and goats slaughtered without stunning would experience pain during the period between the neck incision and the onset of insensibility after slaughter.

Assessment of the interval between the neck incision and insensibility

The interval between the neck incision and the onset of insensibility determines the period during which pain may be experienced after the incision.

Insensibility

The reported intervals between neck incision and the onset of insensibility depend on the precise definition of the terms used to describe insensibility in different studies, and occur against a background of anatomical differences in the cerebral vasculature. These differences result in findings regarding this interval not being readily transferrable between ruminant species.

Definitions of terms used in this context are often imprecise. For the purposes of this review, the following terms will be used. Awareness means the capacity to experience sensations, including unpleasant sensations such as pain. Insensibility means a complete inability to experience any sensations, i.e. a complete absence of awareness.

The purpose of the neck incision is to kill the animal. It severs major blood vessels supplying and draining the brain and this causes a catastrophic decrease in cerebral blood flow and eventually brain death. In non-stunned animals it is the lack of oxygen due to this loss of blood flow to the brain that causes the onset of insensibility (Gregory 2004; Mellor and Littin 2004). The interval between the neck incision and the onset of insensibility determines the period during which pain may be experienced after the incision. The progression towards cessation of cerebral perfusion after transecting the carotid arteries depends on between-species anatomical differences in the vascular supply to the ruminant brain.

Blood supply to the brain

In most mammalian species arterial blood is supplied to the brain via two channels. Most of the blood travels through the internal carotid artery, which is a branch of the common carotid artery, and this supplies tissues as caudally located as the occipital lobe of the cerebral cortex. The part of the brain caudal to this receives its blood from the basilar artery, a branch of the vertebral artery, in which blood flows in a rostral direction. However, this is not the case in ruminants and in some other mammals such as the cat, which do not have an intact internal carotid artery (Gillilan 1974; King 1987).

In sheep, all the blood that perfuses the arterial circle (Circle of Willis) of the brain arrives via an anastomosing ramus of the maxillary artery, which is a branch of the external carotid artery. Blood flows in a caudal direction in the basilar artery and so no blood originating from the vertebral arteries reaches regions of the brain cranial to the caudal part of the medulla oblongata. In cattle and goats, however, there is an additional supply to the arterial circle via a branch of the vertebral artery. This means that both carotid and vertebral arterial blood perfuses the whole of the brain in these animals (Gillilan 1974; King 1987; Antognini and Schwartz 1993).

Interrupting blood supply to the brain

When the carotid arteries are transected, both cut ends provide a low-pressure route by which blood drains from the circulation. Thus, it is likely that most of the blood flowing towards the brain in the vertebral arteries will, after carotid transection, flow away from it towards the rostral stump of the cut arteries. This altered blood flow is likely to be greater in animals that have a patent internal carotid artery, because this vessel will provide a low resistance route between the arterial circle and the distal transected end of the common carotid artery. This will reduce pressure in the arterial circle and so prevent perfusion through the arteries leading from the arterial circle to the tissues of the brain. However, as this artery is absent in ruminants, there may be greater potential for some vertebral blood to perfuse the brain via the arterial circle. This is thought to be more likely in cattle and goats than in sheep because, as already noted, they possess a low resistance pathway between the vertebral artery and the arterial circle of the brain. However, after carotid transection in sheep, vertebral blood could only arrive at the brain if flow in the basilar artery was reversed, an improbable occurrence as the basilar artery is likely to be a relatively high resistance pathway.

In all animals the possibility of occlusion of the rostral stump of the carotid artery would remove the low-pressure exit route for vertebral blood and could result in the maintenance of brain perfusion. Occlusion of the arterial stump, a relatively common occurrence in some species, is characterised by retraction and contraction of the elastic portion of the arterial wall and thrombus formation around the cut end of the vessel (Gregory *et al.* 2006, 2010, 2012). Animals can routinely survive the occlusion of one common carotid artery (Clendenin and Conrad 1979) and so it is likely that a single occluded stump would result in continued brain perfusion until sufficient blood had been lost to cause the systemic arterial blood pressure to collapse.

These species differences in the anatomy of the cerebral arterial supply mean that it is not possible to draw conclusions about time to loss of brain perfusion or onset of insensibility from experimental data recorded in other species, although it is likely that awareness will be longer-lasting in cattle and goats than in other species.

Methodological approaches: strengths and limitations

The assessment of the precise point after slaughter at which non-stunned animals become insensible to pain has been and remains a major methodological challenge. Although attempts have been made using changes in different features of brain electrical activity and behavioural changes, there remain interpretational limitations with these. As noted by Tidswell *et al.* (1987), there are no definitive methods for determining the exact time of onset of insensibility during the slaughter process, and this is still true today. The following is a brief outline of methodologies that have been employed in different studies.

Electroencephalogram

EEG morphology

Following neck incision, the EEG changes gradually from a normal to an isoelectric pattern. Similar morphological changes have been reported in cattle (Bager *et al.* 1992), sheep (Nangeroni and Kennett 1964; Gregory and Wotton 1984; Devine *et al.* 1986) and goats (Nangeroni and Kennett 1964). A number of researchers in early studies have attempted to categorise the intermediate stages in this progression and have speculated about which stages indicate awareness and which insensibility. Nangeroni and Kennett (1964) used unspecified morphological changes to determine insensibility. Newhook and Blackmore (1982) identified three categories: active EEG, transitional EEG and isoelectric EEG. They considered that active EEG reflected awareness and that transitional and isoelectric EEG patterns indicated insensibility. Subsequent researchers have used categorisations based on those of Newhook and Blackmore (1982). Examples of studies using these categorisations include Gibson *et al.* (2009c) and Kongara *et al.* (2014).

Evoked responses

Evoked responses are EEG patterns recorded in response to a rapidly repeating stimulus that may be visual, auditory, tactile or painful. The losses of these responses have been used as indicators of insensibility, but can be difficult to interpret because mathematical amalgamation of multiple responses is often necessary to detect them against background EEG activity (Murrell and Johnson 2006). In addition, the response to a repeated uniform stimulus can decrease over time in a stable preparation (Gibson 2009). Finally, evoked responses change in different ways with different neurological manipulations. For example, they can be recorded under very deep anaesthesia with some agents (e.g. thiopentone, propofol), but are abolished under light anaesthesia with others (e.g. halothone) (Huatori *et al.* 2004; Gibson 2009). Gregory and Wotton (1984) recorded visual evoked responses following slaughter by neck incision of anaesthetised sheep.

Behaviour

Behaviour has been used as an indicator of the onset of insensibility, but interpretation of each selected behaviour may be equivocal unless supported by other information (Blackmore 1984).

Collapse

Collapse occurs when a freely standing animal falls to the ground. This is the earliest indication of approaching insensibility after the neck incision (Blackmore 1984; Grandin 1994), but should be used with caution as animals can show signs of conscious behaviour following collapse. More recently a study of 174 cattle found that 14% of them regained their feet following initial collapse (Gregory *et al.* 2010).

Loss of righting reflex

This occurs when a recumbent animal that attempts to regain its feet ceases to do so. It has been suggested that this may indicate loss of sensibility (Blackmore 1984).

Clonic convulsions

Clonic convulsions are a form of seizure characterised by insensibility and rhythmic alternate involuntary contraction and relaxation of muscle groups. Following slaughter by neck incision, such convulsions are due to advanced cerebral hypoxia and loss of function (Blackmore 1984; Grandin 1994). Some researchers have used the time from the neck incision to the onset of such convulsions as an unequivocal indicator of definite insensibility (Gibson *et al.* 2009c). These authors acknowledge that actual insensibility would have begun earlier than this time, but state that this is the point in time after which there is no possibility of sensibility.

Quantitative estimates of the interval to insensibility

There have been several investigations of the interval to insensibility following slaughter by neck incision based on analysis of the EEG. The findings of studies in sheep, cattle and goats are summarised in Table 2. In considering these sources, it must be remembered that they were produced between 25 and 50 years ago. In the earliest sources, details of the methodology used, and in some cases the way in which the results are reported, are not fully clear. As an example, Nangeroni and Kennett (1964), is usually quoted as the seminal reference in this area. The source document is a two-paragraph entry in the Annual Report of New York State Veterinary College. It refers to sheep, goats and cattle, but does not state how many animals were used either of each species or in total and reports subjective EEG observations without indicating if the figures given are ranges or some other measure of variability.

Blackmore (1984), reported behavioural changes in five calves, one bull, three lambs and two ewes. The results are summarised in Table 3. More recently, Gregory *et al.* (2010) reported time to collapse in 174 cattle. The mean time to final collapse for all the cattle was 20 (SD 33) seconds. In 8% of the animals time to final collapse was 60 seconds or more.

In this review we have presented the existing data at face value and present overall estimates of times to insensibility as ranges that encompass the findings of all of the sources used. Taken together, these studies contained no unequivocal estimate of the interval to insensibility. The shortest estimate is based on loss of ability to stand at 2–4 seconds and the longest estimate is based on time to onset of clonic convulsions at 68–158 seconds (Blackmore 1984). The estimates based on EEG measurements all fall between these two extremes.

Conclusions about welfare risks

The research reviewed above represents an incomplete picture of the events surrounding slaughter by ventral-neck incision, but there is sufficient information to allow a number of conclusions to be drawn confidently. These conclusions and related inferences are given below prior to providing a final analysis of the welfare risk of slaughter by ventral-neck incision without prior stunning.

Conclusions about the neck incision and pain

Studies by Gibson *et al.* (2009a) demonstrated a cerebral response to ventral neck incision in anaesthetised cattle that was similar to the response to surgical dehorning (Gibson *et al.* 2007). This indicates that ventral neck incision is a noxious stimulus and

Table 2. Summary of studies using analysis of electroencephalographic (EEG) data to determine interval to insensibility following slaughter by neck incision in sheep, cattle and goats.

EEG criterion used to determine insensibility	Time after incision (seconds)	Number of animals	Reference
Sheep			
Normal EEG (as indicator of continued sensibility)	3.5–5	Unknown	Nangeroni and Kennett (1964)
Short period of high potential discharge	Began at 12–15		
Amplitude below 10 µV	By 2–7	10	Newhook and Blackmore (1982)
Amplitude below 10 µV	By 8–22, 13.6 ± 7.4 (mean ± SD)	10	Devine *et al.* (1986)
Amplitude below 10 µV	By 7	1, neck incision	Tidswell *et al.* (1987)
Isoelectric	By 48		
Amplitude below 10 µV	By 8	1, decapitation	
Isoelectric	By 20		
Loss of visually evoked responses	At 14 (mean), by 22 sec (95% upper CI)	20	Gregory and Wotton (1984)
Cattle			
Normal EEG (as indicator of continued sensibility)	3.5–5	Unknown	Nangeroni and Kennett (1964)
Short period of high potential discharge before cessation of EEG	Began at 12–15		
Amplitude below 10 µV	34 in one animal, 65–85 in all others	8 calves	Newhook and Blackmore (1982)
Amplitude below 10 µV	28, 30 and 168	3 calves	Blackmore *et al.* (1983)
Amplitude below 10 µV	9–85	8 adult cattle	Daly *et al*. (1988)
Loss of visually evoked responses	17 ± 4 (mean ± SD)	8 calves	Gregory and Wotton (1984)
Goats			
Normal EEG (as indicator of continued sensibility)	3.5–5	Unknown	Nangeroni and Kennett (1964)
Short period of high potential discharge before cessation of EEG	Began at 12–15		

represents very strong evidence that this would be perceived as painful in the period between the time of the incision and the time of loss of awareness (Mellor *et al.* 2009). There are currently no direct data that demonstrate this in sheep or goats, but the physiological similarities between sheep, goats and cattle indicate that slaughter by neck incision in non-stunned ruminants will cause pain in the same way.

Conclusions about the time to insensibility

The precise assessment of the point after slaughter at which the animal becomes insensible has been and remains a fundamental challenge in understanding the progression of this salient cerebral process in non-stunned animals at slaughter.

It is clear that slaughter by neck incision does not render ruminants immediately insensible. Sheep may remain aware for at least 2–8 seconds following the transection of major blood vessels of the neck. Cattle may commonly remain aware for as long as 85 seconds or even longer in some individuals, the longest recorded duration of awareness in cattle based on EEG studies is 168 seconds. There are currently insufficient data to be able to estimate the likely duration of awareness in goats.

When correctly applied, stunning prior to slaughter renders animals instantaneously insensible in the case of captive bolt, free bullet and electrical methods and rapidly insensible in the case of other commonly used techniques such as hypoxic gas mixtures (Webster 2005). In all cases, animals are insensible at the

Table 3. Summary of behavioural observations of sheep and cattle following slaughter by neck incision.

Behaviour	Mean (SD) time after incision (seconds)	Range (seconds)	N	Reference
Loss of ability to stand	41 ± 11	5–135	5 calves	Blackmore (1984)
Loss of apparently coordinated attempts to rise	172 ± 36	30–385		
Pupil dilation	332 ± 30	140–455		
Onset of clonic convulsions	Only seen in two animals	160 and 460		
Loss of ability to stand	3 ± 0.4	2–4	3 lambs	Blackmore (1984)
Loss of apparently coordinated attempts to rise	9 ± 0.6	8–11		
Pupil dilation	80 ± 11.1	56–114		
Onset of clonic convulsions	119 ± 17.5	68–158		
Loss of ability to stand	3 (slipped and fell)		1 bull	Blackmore (1984)
Loss of apparently coordinated attempts to rise	20			
Pupil dilation	15			
Onset of clonic convulsions	440			
Final collapse	20 ± 33	>60 in 8%	174 cattle	Gregory *et al.* (2010)

time of neck incision and so there is no possibility that this could be painful and represent a compromise to their welfare.

Overall conclusions

Taken together the conclusions above indicate that because the slaughter of ruminants by ventral-neck incision without prior stunning is likely to cause pain, such slaughter without prior stunning poses a risk to animal welfare in the period between the time of the neck incision and the time of loss of awareness. The duration of this period of risk is not currently known with certainty. In sheep it is at least 2–8 seconds, but may be 8–20 seconds in duration. In cattle the duration is much longer, commonly up to 85 seconds with occasional instances of much longer durations of awareness.

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