METHODS USED TO KILL FISH: FIELD OBSERVATIONS AND LITERATURE REVIEWED

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Abstract *Animal Welfare 2002, **11**: 269-282*

This paper reviews the impact on fish welfare of a wide range of slaughter methods used commercially around the world. Because the end result of the slaughter is a food product, and because of the well-known relationship between an animal's welfare and subsequent meat quality, the effects of the slaughter methods on the quality of the flesh are also reviewed where possible. Fish slaughter methods are incredibly diverse, but fall into two broad categories: those that induce loss of sensibility slowly, and those that achieve this rapidly. This paper shows that, in general, the methods that induce loss of sensibility over a long period of time tend to impinge more on the welfare of the animal and are detrimental to the overall quality of the carcass. Methods that cause a rapid loss of sensibility result in the best welfare, providing that they are carried out correctly. They may also produce the highest quality product from the stock of fish.

Keywords: *animal welfare, fish, harvest, killing, quality, slaughter*

Introduction

In order to kill animals humanely, they must either be rendered unconscious immediately, or, if unconsciousness is induced progressively, then the induction phase should be without pain or fear (MAFF 1995). The established ways of achieving this in farmed mammals and birds are to render them immediately unconscious by a physical blow to, or passage of an electrical current through, the head (stunning); or, to induce unconsciousness gradually with a hypoxic or anaesthetic gas. Once the animal is unconscious, its death is usually achieved by exsanguination (bleeding). In practice, stunning methods can be subject to poor application (Anil & McKinstry 1998), and preslaughter handling can expose animals to poor welfare (Warriss 1998; Warriss *et al* 1998).

Most slaughter methods used on farmed fish have been developed to meet the market requirements for ease of operation, maintenance of adequate carcass quality and cost. To date, the welfare of the fish has been of little concern. Many of the methods used to kill fish do not appear particularly humane, and some would not be considered acceptable for most other food animals. Increasing public concern for animal welfare is resulting in a reassessment of fish killing procedures. These changes in values are reflected in the report of the Farm Animal Welfare Council (FAWC 1996) and the draft recommendation concerning farmed fish shortly to be published by the Council of Europe. These documents express the opinion that the principles of humane slaughter, which are applied to farmed birds and mammals, should also be applied to fish. Thus, in line with changing public perceptions, it is important that fish killing systems also take into account aspects of animal welfare.

The welfare of fish at slaughter is an important subject, but there are no published reviews. The purpose of this paper is to describe the methods used to kill fish and to review information on the consequences to welfare of these methods. Because carcass quality is commercially important and can determine acceptability of killing systems regardless of welfare, the effect of fish killing methods on carcass quality is also briefly reviewed where appropriate. Relatively few accounts of fish killing are present in the scientific literature and it has been necessary to draw on a considerable body of grey literature, such as unreviewed reports, unpublished papers, experience of relevant professionals and our own field observations. Unreferenced statements in this review refer to our own field observations.

Fish slaughter methods have been grouped into methods that do not cause immediate loss of consciousness (slow methods) and methods that do cause immediate loss of consciousness (fast methods). For each procedure, a description of the method is followed by a summary of the effects on welfare and on carcass quality.

Methods that do not cause immediate loss of consciousness (slow methods)

These methods tend to be used to kill fish in bulk, with fish being processed rapidly and with little manual effort. As such, they are relatively cost-effective in terms of time and labour.

Asphyxiation

Most species of fish die when held in the air for a period because their capacity for gaseous exchange is compromised when the gill lamellae collapse. Asphyxiation by removal from water is probably the most common method used for killing fish around the world. Smaller farmed fish with low individual values, such as trout (*Oncorhynchus* spp. and *Salmo trutta*) or tilapia (*Oreochromis* spp.), tend to be killed by this method. The time required for the fish to die is dependent both on species and on temperature (Table 1). Some species adapted to spending periods of time out of water, such as eels (*Anguilla* spp.), can survive for a very long time when removed from water. However, most fish die faster at higher temperatures. This is probably because their metabolic rate is dependent on temperature, and oxygen supplies are used up faster at higher temperatures.

Table 1 Effect of temperature and species on time to loss of brain function, as measured by loss of visual evoked responses.

Species	Temperature (°C)	Time to loss of brain function (min)	Reference
Rainbow trout	2	9.6	Kestin *et al* 1995
	14	3.0	Kestin *et al* 1995
	20	2.6	Kestin *et al* 1995
Gilthead sea bream	0.1	5.0	Robb, unpublished
	22	5.5	Robb, unpublished

Fish lose sensibility before carcass movement is lost. Carcass movements were shown to continue for 28.6 min whilst sensibility was lost after 3.0 min in trout killed at 14°C in air (Kestin *et al* 1991). Similarly, carcass movements continued for 11.1 min whilst sensibility was lost after 2.6 min in trout killed at 20°C in air (Kestin *et al* 1991). Thus, the duration of carcass movement is not a good indicator of the duration of potential suffering. Removing fish from water is highly aversive to them. In most cases, violent attempts to escape are made and a maximal stress response is initiated. The procedure is widely used as an experimental stressor in studies of the stress response of fish (Donaldson 1981).

As asphyxiation is so commonly used to kill fish, it must be assumed that fish killed by this method are of a quality that is generally commercially acceptable. Kestin *et al* (1997) found almost no haemorrhages in fish killed by asphyxiation, in contrast to those killed by electrical stunning. However, there may be other unreported deleterious effects on fish quality of killing them by asphyxiation. The fish make vigorous attempts to escape, and Mochizuki and Sato (1994) report that horse mackerel (*Trachrus japonicus*) killed by asphyxiation show increases in the rate of lactic acid production and the rate of loss of ATP post mortem, with consequent earlier entry into rigor mortis, compared to fish killed by immersion in ice slurry or by severing the spinal cord. The implications of these findings for carcass quality are reviewed in the Discussion section.

Asphyxiation in ice

Farmed fish are also commonly asphyxiated in ice or an ice/water slurry. To achieve this, the fish are either added to the ice/water slurry, or are packed live in flake ice. If added to an ice/water slurry, the water is usually drained off after approximately 10 min, or after all fish movement has ceased. This killing method is commonly used for farmed species such as rainbow trout (*O. mykiss*; Kestin *et al* 1991), gilthead sea bream (*Sparus auratus*), sea bass (*Dicentrarchus labrax*; Smart 2001), barramundi (*Lates calcarifer*; Frost *et al* 1999) and channel catfish (*Ictalurus punctatus*; Boggess *et al* 1973).

Temperate fish take longer to lose brain function when killed in ice than in air. For example, rainbow trout killed in ice slurry took 9.6 min to lose brain function, compared with 3.0 min when killed in air at 14°C (Kestin *et al* 1991) (Table 1). It is thought, however, that if the differential between the ambient temperature of the fish and the ice is relatively great, thermal shock may shorten the time to loss of brain function. For example, in a study where sea bream from the Mediterranean, with an ambient temperature of 22°C, were killed in air or ice slurry, both groups of fish lost sensibility at approximately the same time. If loss of sensibility had followed the same pattern as trout, the group killed in ice slurry would have been expected to retain brain function for much longer than the fish killed in air. Thus thermal shock may have played a role in shortening the time to loss of brain function in this species. More work is required in this area to confirm the effect. Loss of brain function resulting from cooling is reversible; if fish are transferred immediately after loss of visual evoked responses (VERs) from iced water to water at normal temperatures, they recover brain function quickly (Robb, unpublished results 1999).

It is not clear how aversive immersion in ice is to fish. It has been proposed that cooling fish in ice slurry could be painful, as immersion of an appendage in iced water has been used as a torture method in humans. Conversely, loss of sensibility resulting from hypothermia is said to be painless in humans. It is not possible to resolve these arguments at this stage. When fish are introduced to water at ambient temperature, they continue to swim actively. When introduced to an ice slurry, however, fish move around within the slurry for only a short period before slowing and becoming paralysed as their muscles cool (some species of fish, such as trout, can acclimatise to water at near freezing point, but this process requires gradual cooling and takes several days). Because of the muscle paralysis caused by cooling, it is not possible to use behavioural indices to determine whether fish find rapid cooling aversive. However, rapid cooling does initiate a stress response (Donaldson 1981; Skjervold *et al* 2001). The paralysis induced by rapid cooling is reversible; when transferred back to water at ambient temperature, fish rapidly regain muscular movement. This has been observed both in gilthead seabream (Robb, unpublished results 1999) and in African catfish (*Clarias gariepinus*), which are not asphyxiated in the ice slurry as they can breath air and so are killed only when filleted (J W van de Vis, personal communication 2001).

One of the reasons cited by producers for using this method is that rapid chilling promotes flesh quality by reducing both autolytic degradation and muscular activity immediately before death (see below for a discussion). However, published reports tend not to support this proposition. Mochizuki and Sato (1994) reported that muscular lactic acid concentrations in fish killed in ice slurry were higher than in fish killed by severing the spinal cord, indicating greater muscular activity ante mortem. Frost *et al* (1999) reported no difference in time of onset of rigor, pH-fall post mortem or flesh texture in barramundi killed in ice slurry or by other methods. Pastor *et al* (1998) also failed to find a difference in total microbial counts between sea bream killed in air or in ice slurry. Further, there appears to be no reason why the fish have to be alive before immersion in ice slurry — any benefits could be obtained equally well if the fish were killed before chilling.

Ante mortem chilling has also been used to immobilise fish before killing by other methods. This is distinct from asphyxia in ice, as the fish are pumped into oxygenated, chilled seawater (at approximately –1°C) with the aim of keeping them alive. Erikson (2001) reports the use of chilled seawater at 1°C for up to 4 h to subdue Atlantic salmon prior to CO_2 narcosis (see below). In this case, the fish were torpid on removal from the chilled water and induction of CO_2 narcosis. However, no effects on flesh quality were reported. Skjervold *et al* (2001) also investigated the use of live chilling of Atlantic salmon prior to slaughter. They showed that live chilling induced a significant rise in plasma cortisol concentration in uncrowded fish; in crowded fish, the mean cortisol level was higher than that of unchilled crowded fish, but not significantly so. Live chilling also resulted in higher lactate concentrations, which implied that the fish showed greater levels of muscle activity. This is known to adversely affect flesh quality attributes (Robb 2001a), although the rapid decrease in temperature may reduce the impact on overall quality compared to other methods resulting in high muscle activity (Skjervold *et al* 2001).

Exsanguination

Many large fish, such as Atlantic salmon (*Salmo Salar*) and tuna (*Thunnus* spp.), are commonly exsanguinated after stunning to improve carcass quality, but exsanguination without stunning is also routinely used in some regions to kill fish, such as salmon (Robb *et al* 2000a) and channel catfish (Boggess *et al* 1973). To achieve exsanguination, the gills are cut or manually pulled out and the fish returned to water to bleed (Wardle 1997). Exsanguination alone is a relatively slow method for killing fish: salmon killed by exsanguination took 4.5 min to lose VERs after gill-cutting without prior stunning (Robb *et al* 2000a). The fish were reported to show clear signs of aversive behaviour for the first 30 s whilst bleeding. The time taken for fish to die by exsanguination appears to be temperature-related, with fish at lower temperatures taking longer to die (Robb *et al* 2000a).

Exsanguination is reported to promote carcass quality by minimising blood spotting in the flesh and improving the colour and taste of the flesh by reducing blood-induced 'off' flavours (Roth *et al* 2001). However, there are no reports that exsanguination without stunning achieves a better bleed-out than exsanguination after stunning. Evidence from red and white meats (Warriss & Wotton 1981; Wilkins & Gregory 1985; Warriss & Wilkins 1986) indicates that freshly killed animals without heart function bleed out as effectively as animals with a functioning heart. Exsanguinating fish after stunning would thus improve welfare without compromising quality.

Carbon dioxide narcosis

CO_2 is highly soluble in water and has a narcotic effect on fish placed in water saturated with the gas. Narcosis in CO_2-saturated water is widely used in Norway to kill or stun salmon prior to exsanguination. CO_2 gas is diffused into a bath of seawater. The pH of the water declines, and when it stabilises at about 4.5 the water is judged to be approaching saturation with the gas (Anon 1995). Fish are then netted or pumped into the water and are left in the bath until movement stops. Industry codes recommend that fish be left in the water for at least 4.5 min before exsanguination (Anon 1995), but observations indicate that fish are often removed as soon as carcass movement stops after 2–3 min.

Loss of sensibility in salmon stunned in CO_2 takes approximately 6 min to induce (Robb *et al* 2000a) but fish that are more resistant to anoxia can survive for much longer. It has been reported that eels show escape behaviour for 1.8 h (Marx *et al* 1997). On immersion in CO_2-saturated water, trout (Kestin *et al* 1995), salmon (Robb *et al* 2000a; Wall 2001), carp and eels (Marx *et al* 1997) show vigorous aversive reactions, swimming very rapidly and making escape attempts. This behaviour lasts for about 3 min in salmon (Robb *et al* 2000a) and trout (Kestin *et al* 1995). Carp, trout and eels are all reported to show signs of increased mucus production during CO_2 narcosis (Marx *et al* 1997), which could be further indication that the process is irritating. Because fish become immobile considerably before loss of sensibility, there is a risk that fish are being exsanguinated whilst still sensible. Indeed, signs of recovery during bleed-out following CO_2 narcosis are regularly observed.

There are many reports that killing fish by CO_2 narcosis results in more rapid post mortem muscle acidification, faster onset of rigor and lower water-holding capacity compared to percussive stunning (Azam *et al* 1989; Marx *et al* 1997; Robb 1998; Frost *et al* 1999; Ottera *et al* 2001). These are all associated with vigorous ante mortem activity, which has been implicated in poorer flesh quality (Robb *et al* 2000b; Erikson 2001; Robb 2001a). CO_2 narcosis has also been reported to result in poorer overall sensory scores in taste tests for eels and carp (*Cyprinus* spp.), compared with electrical stunning or percussive stunning (Marx *et al* 1997).

There is anecdotal evidence that in Norway some salmon and trout are killed in CO_2-saturated water to which ice has been added, thus combining the killing methods of CO_2 narcosis and asphyxiation in ice. A higher concentration of CO_2 can be achieved by diffusing the gas into chilled seawater, but as CO_2 gas is highly soluble in water at room temperature this is unlikely to have major effects. There are no reports of the welfare or quality consequences of this killing method but adding ice will cool the fish, which may benefit microbial and autolytic degradation.

There is also anecdotal evidence that fish have been slaughtered in CO_2-saturated water to which oxygen has also been added, and that fewer aversive reactions are seen than when they are killed in CO_2-saturated water alone. However, there is no information on the welfare or quality consequences of this killing system.

Evisceration

Evisceration of live fish without prior stunning occurs during the processing of wild caught fish on commercial fishing boats. Evisceration methods vary with species, and can be confined to partial removal of the intestinal tract (herring, *Clupea harengus*), to removal of the liver and intestinal tract (flat fish such as turbot, *Psetta maxima*), or to removal of all viscera and heart (for example cod, *Gadus morhua*). Death is caused by a combination of exsanguination and asphyxiation. The time for which fish survive following evisceration depends on the species and the treatment, varying from about 20 min for pelagic fish such as herring and cod to 40 min for demersal fish such as plaice (*Pluronectus platessa*) (J W van de Vis, unpublished results 1998). There are no reports on the quality implications of live evisceration, but as it is widely practised on fishing boats the quality must be generally acceptable.

Decapitation

Decapitation is currently used as a means of killing eels, which are notoriously hard to kill. Eels are held on a board and the head is completely severed. Because of the proximity of the heart and the brain, the heart is usually severed with the head. Verheijen and Flight (1997) reported loss of reactions to painful stimuli in eels 13 min after decapitation. However, up to 27 min elapsed before loss of VERs (Robb, unpublished results 2000). Decapitation is unsuitable as a killing method for other species of fish as their body shape prevents its easy application. There are no reports of the quality implications of decapitation.

Anaesthetics

Food-grade fish anaesthetics or sedatives based on eugenols such as clove oil have recently been developed and marketed for use in killing fish. One particular combination is marketed under the trade name AQUI-S™ (AQUI-S New Zealand). When introduced into the water at an approximate concentration of 17 ppm, salmon lose motor function and responsiveness after about 30 min (Robb *et al* 2000b). The fish are then netted and killed by percussion or spiking and show no physical activity or aversive reactions to handling (Robb 1998; Goodrick *et al* 1998). AQUI-S™ is used commercially in Australia and New Zealand as a preslaughter sedative during salmon killing. Fish such as eels, which are resistant to anaesthetics, require higher concentrations of eugenol (van de Vis *et al* 2001). It is not clear whether these compounds have true anaesthetic properties and induce insensibility, or whether they are merely sedative in action, but fish sedated before slaughter appear to suffer far less distress than untreated fish when removed from water for stunning.

There are several reports that certain aspects of flesh quality in salmon and rainbow trout killed after sedation with AQUI-S™ are improved. Muscle activity immediately before slaughter is substantially reduced, and thus the post mortem pH-fall is slower. In salmon, this leads to a slower onset of rigor, a redder colour and less gaping (Goodrick *et al* 1998; Robb *et al* 2000b), and also increased muscle-fibre strength (Jerret *et al* 1996). In eels, the post mortem drop in muscle pH is also slower, and the flesh is of higher quality and lasts longer before rejection by a taste panel (van de Vis *et al* 2001). These are all features associated with relatively little muscular activity ante mortem and with better flesh quality (Robb 2001a). However, there are concerns that fish killed with these compounds could be tainted with a clove oil flavour. AQUI-S™ does not currently have a product licence for use on fish at slaughter in Europe or the USA.

Salt or ammonia bath

Eels are difficult to kill, and in Holland and Germany it has been commercial practice to kill them by immersing them in a bath of dry salt or ammonia solution. The main purpose of the salt or ammonia is to aid removal of the slime from the fish, but it also renders the fish immobile and suitable for processing (van de Vis *et al* 2001). Eels make extremely vigorous attempts to escape from a salt bath that can last up to 30 min (Kestin *et al* 2002). Eels killed in salt take a long time to lose sensibility (Robb, unpublished results 2000) and it is probable that movement stops because of muscular exhaustion. Killing eels in salt is now considered inhumane in Germany and since April 1999 has been banned under a directive to protect eels at slaughter (Bundesgesetzblatt 1993).

Anoxic water bath

Experimental attempts have been made to kill fish in water from which all the oxygen has been removed, either by degassing the water or by displacing the oxygen with an inert gas such as nitrogen or argon. These studies have shown that it is difficult to remove sufficient oxygen from the water for insensibility to be induced in a reasonable period of time (Kestin *et al* 1997). Maintenance of the anoxic water is also difficult, because fish activity and the process of adding the fish enable atmospheric air to become dissolved in the water. In these studies, the fish showed aversive reactions during induction of insensibility; however, these were less severe than those shown by fish killed by CO_2 narcosis.

Electro-immobilisation and electro-stimulation

In this section, electrical processes that do not render fish insensible immediately are discussed. Electrical stunning is covered in the section 'Methods that cause immediate loss of consciousness (fast methods)'.

An electrical killing system widely used in Denmark to kill trout passes a low-voltage (sub-stunning) alternating current (a.c.) waveform through a solid mass of live fish for several minutes. The fish are electro-immobilised through electrical stimulation of the muscles. The muscles of the fish become completely exhausted and the fish are immobile when they are processed 10 min later. The current does not render the fish insensible and, as electrical shocks are painful, may expose the fish to considerable suffering. There are no reports of the consequences for carcass quality of this killing method. However, energy-reserve depletion caused by electrical stimulation leads to conditions of low pH immediately post mortem and rapid onset of rigor (Azam *et al* 1989), similar to fish that have undergone vigorous exercise immediately ante mortem (Robb *et al* 2000b). Thus, fish killed by this method are likely to suffer similar welfare and quality consequences to those outlined in the following section.

Electro-fishing

This technique is widely used to catch fish from freshwater rivers and canals. A pulsed direct current is passed through a body of water and fish are attracted to the cathode by galvano-taxis. The fish become electro-immobilised as they enter areas of high field density and float to the surface where they are netted out. No information on the effect of electro-fishing on the level of sensibility is available, but the fish recover immediately when they are put back into fresh water. Fish that have been collected by electro-fishing show a maximal stress response (A D Pickering, personal communication 2001), and as electro-fishing involves passing an electric current through fish that are not insensible, there are grounds for believing that this method exposes fish to considerable suffering. Carcass quality problems, including broken vertebrae and haemorrhages, are routinely reported from fish that have been collected by electro-fishing (Sharber *et al* 1994).

Methods that cause immediate loss of consciousness (fast methods)

These methods tend to be applied to fish individually, and as such can be relatively time consuming and labour intensive.

Percussive stunning

This method is commonly used in the salmon industry (Anon 1995), by halibut fish farmers (Aske & Midling 2001), by commercial fishermen (Kramer & Paust 1988) and by anglers to kill fish. The fish are removed from the water, restrained, and a blow or blows are delivered to the head by a rapidly moving club. Typically, fish are out of water for about 10 s before the blow is administered. The blow is usually applied manually, although automatic percussive stunning devices are becoming available. When the blow is correctly applied and is of adequate force, loss of movement and VERs is immediate (Kestin *et al* 1995; Marx *et al* 1997; Robb *et al* 2000a). When applied incorrectly, or with insufficient force, insensibility is not immediate (Kestin *et al* 1995; Robb *et al* 2000a) and injuries to the fish can result. Percussion is not a suitable method for killing some species of fish such as sea bream, catfish or eels (van de Vis *et al* 2001).

There are consistent reports that fish killed by percussive blows show reduced physical activity at slaughter, slower post mortem muscle acidification and slower onset of rigor (Azam *et al* 1989; Marx *et al* 1997; Robb 1998). These are all features associated with relatively little muscular activity ante mortem and with better flesh quality (see Discussion).

Hydraulic shock

There are numerous accounts of explosive devices being used to kill fish and the welfare and quality implications of this killing method have been investigated (Kestin 1996). In these trials, providing that the fish were sufficiently close to the detonation (within the stunning range), the shock wave resulted in a stun; however, serious carcass damage in the form of haemorrhages within the flesh was caused in areas adjacent to gas vesicles (eg the swim bladder and gut). The carcass damage incurred by the fish was of such a magnitude to have adversely affected the overall quality of the fish, mainly by haemorrhages within the flesh. Fish exposed to the shock wave beyond the stunning range were disabled and suffered internal damage which would probably have been fatal, but were not rendered insensible.

Spiking, coring and ike jime

These are all terms used to describe killing methods based on inserting a spike into the brain (either manually or using a machine). The method was originally developed for use on large high-value fish such as tuna, but it is also used on salmon (S Frost, personal communication 1999). The fish are lifted from the water and a spike driven into the brain through the top of the head. In some cases the fish are subsequently pithed with a rod or wire to destroy the upper part of the spinal cord and reduce carcass convolutions (A Smart, personal communication 2001). The period between capture and removal from water can vary from about 10 s up to 1 min. When correctly and accurately applied, immediate loss of movement and sensibility is observed in salmon and eels (Robb *et al* 2000a; van de Vis *et al* 2001). Because accuracy is important, anatomical markers that allow the brain to be targeted accurately, such as the pineal window in tuna, are important. Fish brains tend to be small, however, and as fish make vigorous attempts to escape during spiking, the system can be prone to misapplication. In this case, fish are injured and disabled but not rendered unconscious (Robb *et al* 2000a). An automatic system for spiking salmon is currently under commercial development.

Fish killed by spiking show reduced physical activity at slaughter, similar to percussively stunned fish, and consequently have slower post mortem muscle acidification and slower onset of rigor (Lowe *et al* 1993; Mochizuki & Sato 1994; Ottera *et al* 2001; van de Vis *et al* 2001).

Shooting

In some industries in Australia and Spain, large tuna are caught with a gaff, pulled to the surface and shot in the head with a twelve bore shotgun or 0.357 Magnum. The period between gaffing and shooting is not known but is likely to be about 30 s. Shooting probably results in immediate death, if the shot is accurate. The system was developed to kill high-value fish quickly to prevent damage and stress during escape attempts. There are, however, reports that the noise of the shotgun detonation elicits vigorous escape attempts from the other fish in the nets (A Smart, personal communication 2000).

Electrical stunning

In this section, electrical processes that induce insensibility immediately are discussed. Electrical stunning of fish has been investigated for several years (Azam *et al* 1989). In most systems, 50 Hz a.c. is passed through a bath of water in which the fish are contained. Providing that the voltage gradient is of sufficient magnitude, loss of movement (Marx *et al* 1997) and VERs is immediate (Kestin *et al* 1995). If the voltage gradient is not sufficiently large to stun the fish, they are immobilised during the current flow and, after the current is turned off, strong aversive reactions are seen (Kestin *et al* 1995). If the fish are stunned and evoked responses lost, they enter a stage of tonic spasms, with typical epileptiform brain activity in the electroencephalogram which lasts approximately 50 s in trout and salmon (Kestin *et al* 1995; Robb, unpublished results 2000). In salmonids, higher currents and longer stun application times are associated with longer periods of insensibility (Robb *et al* 2000c; Robb *et al* 2002). If all stun parameters are adequate, the fish die without regaining consciousness (Robb *et al* 2002). Eels have been shown to be particularly resistant to electrical stunning and require high currents for at least 5 min to achieve reasonable periods of insensibility (van de Vis *et al* 2001).

During electrical stunning, strong muscle contractions are induced by direct electrical stimulation of the muscles. In salmonids, these muscle contractions induce a lower muscle pH immediately post mortem (Azam *et al* 1989; Marx *et al* 1997), similar to fish that have undergone vigorous exercise immediately ante mortem (Robb *et al* 2000b). Thus, fish killed by this method may suffer reduced carcass quality in the same way as fish killed after vigorous exercise for the reasons outlined in the discussion. Of greater concern is the increased prevalence of carcass haemorrhages widely reported after electrical stunning (Kestin *et al* 1997). However, recent studies indicate that carcass haemorrhages can be minimised if higher frequencies or longer current application times are used (Robb *et al* 2000c; Robb 2001b) or if the current is confined to the head of the fish (Kestin *et al* 1997). Electrical stunning does not appear to cause carcass quality problems in eels (van de Vis *et al* 2001).

Discussion and animal welfare implications

A remarkable variety of methods are used to kill fish, and these have a wide range of effects on welfare and quality (for a summary, see Table 2). At first glance, it is difficult to understand how some killing methods have gained acceptance, as they appear so clearly to be aversive to the animals. However, fish killing has become an industrialised process and concern for the suffering of individuals is frequently lost when animal handling processes become industrialised (Webster 1994). In the case of fish, this is compounded by the widely held belief that 'lower' life forms are incapable of suffering (Bermond 2001). However, this view is being increasingly challenged (Sherwin 2001). There is therefore a growing need to assess fish killing processes and to select those that limit suffering.

Table 2 Summary of the negative impacts on welfare and quality shown by the different slaughter methods.

Method	Negative impact on welfare	Negative impact on quality
Asphyxiation	High	High
Asphyxiation in ice	High	Low
Exsanguination	Very high	High
Carbon dioxide narcosis	High	High
Evisceration	Very high	High
Decapitation	Very high	—
Anaesthetics	Very low	Very low
Salt or ammonia bath	Very high	High
Anoxic water bath	High	—
Electro-immobilisation	Very high	Very high
Percussive stunning	Low	Low
Hydraulic shock	Very low	Very high
Spiking, coring, ike jime	Low	Low
Shooting	Low	Low
Electrical stunning	Very low	Low

— indicates insufficient evidence.

From a welfare standpoint, the important concern with killing processes is the amount of pain or fear that the animal is exposed to before loss of consciousness. There is concern that killing methods that induce insensibility gradually could expose the fish to extended periods of suffering if the process were aversive or painful. With the exception of fish killed after sedation with anaesthetics, there is good evidence not only that fish find slow killing processes aversive (many result in a maximal stress response, as reviewed in Donaldson 1981), but also that they remain conscious for periods extending to several minutes in most cases. Some killing methods, particularly evisceration, salt bath, exsanguination and electro-immobilisation, appear to cause considerable suffering for extended periods of time. There is also a risk that when applied in the commercial situation, slow killing methods expose fish to overcrowding and conditions of low oxygen tension, which could further add to their distress. Thus, with the possible exception of sedation with anaesthetics, all slow killing methods are likely to expose fish to poor welfare at some stage of the process. Legislation in Germany has moved to try to reduce the application of such slow methods. Since April 1999, the use of salt and aqueous ammonia in the process of killing eels has been banned, with percussion stunning and electrical stunning being the only acceptable methods (Bundesgesetzblatt 1993).

Several of the fast killing methods have the potential to induce insensibility with minimal pain or fear. However, in the commercial situation it is usually necessary to restrain and position the fish so that energy can be delivered to its brain. Thus, in practice, some suffering is caused by most fast methods. In many cases, the methods of restraint expose the fish to aversive and in some cases painful situations. For example, salmon that are stunned percussively are removed from the water and restrained by hand before stunning, and tuna that are cored or shot are restrained with a gaff with their head out of the water before stunning. Suffering should, however, be limited to the period between the removal of the fish from the water and the delivery of the blow or shot. If the fish can be retained in the water during stunning, as is the case with electrical stunning or hydraulic shock methods, it may be possible to prevent suffering completely.

Immediate killing methods can also be prone to misapplication or misadventure. For example, in some cases the percussive blow used to stun salmon can be insufficiently powerful to stun the fish; or during spiking, the brain can be missed (Robb *et al* 2000a). In both these cases, the fish will suffer injury but will not be rendered insensible. However, providing that the stunning procedure is correctly applied, fish killed by immediate killing methods will suffer for substantially shorter periods than fish killed by slow killing methods.

Based on the above, the aim of any killing system should be to reduce exposure of the fish to aversive situations before loss of sensibility. To limit exposure to aversive situations, insensibility should be induced as rapidly as possible, and certainly before any invasive procedure such as exsanguination is attempted. There is also a need to ensure that the stunning procedure is irrecoverable, so that fish do not recover sensibility after other procedures such as exsanguination or evisceration have been carried out.

Whatever killing system is used, in order to limit suffering it is important that its effectiveness be monitored. The speed of induction of insensibility can be assessed using, for example, simple tests of sensibility, as outlined in Kestin *et al* (2002), and the aversiveness of the process can be tested using simple behavioural indicators of aversion such as escape behaviour or vigorous swimming activity, as outlined in Kestin *et al* (1995). If a great deal of physical activity is associated with the implementation of the slaughter procedure, it is highly likely that the animals find the procedure aversive. However, because some killing methods such as CO_2 narcosis, asphyxiation in ice and electro-immobilisation can induce immobility before loss of sensibility, caution should be applied before interpreting lack of movement as evidence that a killing method is not aversive. Ideally, these observations should be supported with neurophysiological measurements.

There is a widely documented relationship between vigorous physical activity before death and high muscular lactic acid concentration immediately after death, resulting in a faster entry into rigor mortis, which is often stronger than normal (Erikson 2001; Robb 2001a). This means that in most cases, fish that show vigorous escape attempts before killing will be more prone to gaping and will have paler flesh, softer flesh texture and lower water-holding capacity than fish that are killed without physical exercise. Fast killing methods are less likely to elicit escape attempts and vigorous muscular activity immediately before death than slow killing methods. Thus, flesh quality problems associated with rapid muscular pH-decline are less pronounced with fast than with slow killing methods. The general relationship between physical activity before death and flesh quality is supported by the findings from fish killed with anaesthetic, which have remarkably good-quality flesh (Jerrett *et al* 1996; Robb *et al* 2000b). Similar relationships between slaughter methods and carcass quality are well documented in mammals and birds (Warriss 2000). In general, more humane handling at slaughter, with reduced stress and physical activity immediately prior to death, results in better carcass quality.

Killing methods can compromise product quality directly if the stunning process also induces damage to the carcass as, for example, electrical stunning can. Muscle haemorrhages associated with electrical stunning are often reported. These appear to be particularly associated with a 50 Hz a.c. sinusoidal waveform. Recent evidence (Robb *et al* 2000c) suggests that it may be possible to reduce this downgrading of quality by using higher frequencies. However, experience with mammals and birds suggests that some level of carcass downgrading is inevitable with electrical stunning, almost regardless of frequency. Damage to fish can also be caused by the confinement and positioning required with some killing methods.

Electrical stunning, when correctly carried out, appears to be a highly effective means of killing fish with the minimum of exposure to aversive stimuli. However, when sub-stunning currents are used, as they are during electro-immobilisation and electro-fishing, fish are likely to be exposed to painful and highly aversive situations for extended periods of time. It is therefore important that when killing systems are designed, they are fully evaluated from a welfare point of view.

Fraser and Matthews (1997) suggest a variety of simple approaches to estimate the suffering induced by procedures. Using this approach, it is possible to derive a ranking for fish killing methods in terms of welfare. Thus salt or ammonia bath, decapitation, evisceration, electro-immobilisation, electro-stimulation, and electro-fishing are probably worse than asphyxiation, asphyxiation in ice, CO_2 narcosis, and anoxic water baths; these are in turn worse than percussive stunning, spiking/coring/ike jime and shooting, which are in turn worse than electrical stunning, hydraulic shock or anaesthetics.

Historically, slow killing methods have been popular for killing fish because they are easy and cheap to apply and can kill fish in adequate numbers. Some trade-off in poorer flesh quality has been accepted because the methods are so efficient. It must be recognised that public opinion in Britain and some other European countries is increasingly hostile to systems that appear to cause pain or suffering to animals. Public acceptance of aquaculture products will be increasingly influenced by the degree to which the industry is perceived to be dealing with fish in a humane manner. Evaluation of slaughter procedures with respect to welfare is therefore increasingly important.

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