Available online at www.sciencedirect.com
SCIENCE DIRECT®
Toxicology Letters 151 (2004) 399–406
Toxicology Letters
www.elsevier.com/locate/toxlet

Review

The traditional categories of fluoroacetate poisoning signs and symptoms belie substantial underlying similarities

Miranda Sherley*

RSPCA Australia, PO Box 265, Deakin West, Canberra 2600, Australia

Received 17 February 2004; received in revised form 14 March 2004; accepted 22 March 2004

Available online 27 April 2004

Abstract

Sodium monofluoroacetate (Compound 1080) has been widely used around the world as a vertebrate pest control agent. Following ingestion of 1080 there is a latent period, during which the compound is metabolised into a toxic form, before the onset of symptoms. The timing of this period varies significantly between species as does the median lethal dose. Traditionally different species have also been classified into groups depending on the primary organ system involved in 1080 toxicosis (cardiac, nervous, or mixed signs/symptoms). However, general acceptance of this method of classification has obscured the fact that several signs of fluoroacetate poisoning are common to most vertebrate species. This paper reviews five decades of literature on the signs/symptoms of fluoroacetate poisoning in vertebrates and concludes that there is little justification for the division of animals poisoned by fluoroacetate into symptomatic groups.

Keywords: Sodium monofluoroacetate; Poison; 1080; Vertebrate pest; Signs; Symptoms

1. Introduction

Sodium monofluoroacetate (Compound 1080) was initially developed for use as a rodenticide in the USA in the 1940s (Chenoweth, 1949). It is now widely used in Australia for the control of a range of vertebrate species including dingoes (*Canis lupus dingo*), dogs (*Canis lupus familiaris*), foxes (*Vulpes vulpes*), pigs (*Sus scrofa*), cats (*Felis catus*), rabbits (*Oryctolagus cuniculus*), rats (*Rattus norvegicus*, *Rattus rattus*), Bennet's (*Macropus rufogriseus*) and rufous (*Thylogale billardierii*) wallabies, and brushtail possums (*Trichosurus vulpecula*) (VPC, 2001). 1080 baiting is carried out in all states and territories of Australia (VPC, 2001), where it plays a role in both conservation and agricultural management. Sodium monofluoroacetate is highly toxic to vertebrates (and is also insecticidal (Notman, 1989; Booth and Wickstrom, 1999)), although the sensitivity of different species varies dramatically, with canids generally showing the greatest sensitivity and amphibians the least (Chenoweth, 1949; Peters, 1952; McIlroy, 1986). Because fluoroacetate is produced naturally by some native Australian plant species (Twigg, 1994; Twigg et al., 1996a,b, 1999) some native Australian herbivores living within the natural distribution of those plant species have evolved an unusually high

* Tel.: +61-2-6282-8300; fax: +61-2-6282-8311.
E-mail address: msherley@rspca.org.au (M. Sherley).

0378-4274/$ – see front matter © 2004 Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.toxlet.2004.03.013

tolerance to fluoroacetate (McIlroy, 1982a; Twigg, 1994). However, this effect is limited to regions of western and northern Australia.

2. Metabolic action

To become active as a poison fluoroacetate must first be metabolised within the body to fluorocitrate (Peters, 1952). Flourocitrate then acts by inhibiting the enzymes responsible for the conversion of citrate and succinate in the tricarboxylic acid cycle (Krebs cycle) (Peters, 1952; Fanshier et al., 1964). The results are that food cannot be broken down for energy by the body's cells, resulting in cell death, and that the concentration of citrate in the tissues and blood rises, creating a general metabolic imbalance (acidosis). Citrate buildup further inhibits glucose metabolism by inhibiting the enzyme phosphofructokinase (PFK) (Duin and Bernem, 1968). Because it takes time for the metabolic conversion of fluoroacetate to fluorocitrate there is a delay from the time that the poison is ingested to the initial onset of signs/symptoms.

Despite a common mechanism of action in all vertebrates it has been observed that different species exhibit markedly different signs of fluoroacetate toxicosis. Discrete symptomatic categories into which poisoned animals may be divided were first described by Chenoweth and Gilman (1946) and are still widely cited to today.

3. Symptomatic categories

The system of classification proposed by Chenoweth and Gilman (1946) was based on a series of experimental poisonings carried out by these authors. In general, they found that both the cause of death and the signs of toxicosis varied by species. The four categories that they proposed were: Class I, where the main effects are on the heart. Class II, where both the heart and the central nervous system are involved. Class III, where the main effect is on the nervous system. Class IV, where there is an atypical response typified by slow shallow breathing and a slow heart rate. Other authors have commented that in general, it is herbivores that exhibit cardiac involvement (Class I), carnivores that show extensive involvement of the central nervous system, dying as a result of respiratory depression (Class III), and omnivores that exhibit both cardiac and central nervous system involvement (Class II) (Egekeze and Oehme, 1979).

4. Herbivores

Chenoweth and Gilman (1946) studied the effect of fluoroacetate on rabbits (*Oryctolagus cuniculus*), goats (*Capra hircus*), and horses (*Equus caballus*). Finding that all three species died as a result of ventricular fibrillation they grouped them together as Class I, animals in which the primary effect of fluoroacetate is on the heart. According to this study rabbits also exhibited motor disturbances "manifested by a sprawling position of the forelimbs with the head placed flat on its side between them" with a small proportion also developing tonic-clonic seizures. Other studies investigating the effect of fluoroacetate on rabbits have also reported neurological involvement including; muscular weakness, convulsive fits, ataxia, and hypersensitivity to noise or disturbance (Foss, 1948; Meldrum and Bignell, 1957; McIlroy, 1982a). Other signs described include depression, lethargy, restlessness and respiratory distress (Quin and Clark, 1947; Foss, 1948; Meldrum and Bignell, 1957; Nwude et al., 1977; McIlroy, 1982a). Where Chenoweth and Gilman (1946) described few signs of poisoning in the horse or goat other than ventricular fibrillation, Quin and Clark (1947) found that these animals exhibited evidence of circulatory collapse including weakness, tachypnoea, cold-sweating, a marked fall in temperature, and a rapid pulse, followed by death from respiratory failure. In contrast, Nwude et al. (1977) described poisoned goats as exhibiting depression followed by restlessness then convulsions.

Other authors have carried out experimental poisoning involving cattle (*Bos taurus*), sheep (*Ovis aries*), and a wide range of Australian marsupial herbivores. In Robison's (1970) report on fluoroacetate poisoning of cattle, he reported that signs of poisoning were extremely consistent, with a slight lethargy preceding sudden urination, staggering, collapse, spasms, "in-place running" and death. The signs observed in sheep include apprehension, anxiety with grinding of the teeth, restlessness, hyperactivity, altered socialisation (sitting apart from the flock), abnormal posturing

(sitting on the rump), depression of ruminal movement, urinary incontinence, weakness, extremely rapid heart rate, feeble pulse, severe respiratory distress with froth emanating from the nose and mouth, muscular spasms, tetanic convulsions, hypersensitivity to nervous stimuli, convulsions with kicking or paddling movements, periods of normalcy between convulsions, and partial paralysis (Quin and Clark, 1947; Meldrum and Bignell, 1957; McIlroy, 1982a; Schultz et al., 1982).

Of the Australian herbivores that have been experimentally poisoned, brushtail possums (*Trichosurus vulpecula*) have been described as becoming lethargic, having shallow respiration, defecating, displaying abnormal posturing, as well as unusual vocalisations, ataxia, hypersensitivity to noise or movements, and convulsions, seizures, or spasms associated with ejaculation (McIlroy, 1982a). Other marsupial herbivores exhibited a range of signs including loss of appetite, abnormal posturing, weakness, lethargy, a lack of alertness, respiratory distress with foaming at the nostrils and mouth, ataxia, convulsions with kicking or paddling motions, and ejaculation (McIlroy, 1982a).

5. Omnivores

Chenoweth and Gilman (1946) found that domestic pigs (*Sus scrofa*) and Rhesus macaques (*Macaca mulatta*) poisoned with fluoroacetate displayed both cardiac and neurological involvement with some animals dying of respiratory failure and others of ventricular fibrillation. They therefore grouped these animals into Class II, animals in which fluoroacetate intoxication results in combined cardiac and nervous involvement. In pigs they described tremors, excitability, a disinclination to move, violent myotonic convulsions, respiratory depression and ventricular fibrillation. It is worth noting that they state that ventricular fibrillation followed or occurred during seizures of central origin. Rhesus macaques experienced twitching of facial muscles, nystagmus, excessive blinking, defecation, and excessive salivation followed by tonic convulsions that were associated with consciousness, and eventually ventricular fibrillation.

Other authors describing the effect of fluoroacetate on pigs and Rhesus macaques found that feral pigs displayed a range of signs including vomiting, lethargy, laboured respiration with foaming at the nostrils and mouth, convulsions, and partial paralysis (McIlroy, 1983a) while Rhesus macaques displayed retching and vomiting, dilation of the pupils, defecation, rotation of the head, spasms of facial muscles, coarse tremors of the head, a lack of alertness, tonic convulsions, and clonic convulsions (Foss, 1948). Convulsions started asymmetrically and spread to involve the entire body (Foss, 1948).

Relatively few omnivorous mammals have been experimentally poisoned with fluoroacetate. However, the effect of fluoroacetate poisoning on bandicoots (members of the family Peramelidae) and striped skunks (*Mephitis mephitis*) has been determined, and humans have also been placed in the Class II symptomatic category (Gajdusek and Luther, 1950). Signs of fluoroacetate toxicosis that have been described in poisoned bandicoots include depression, slowed breath rate, trembling, vomiting, hypersensitivity to stimuli, and convulsions (McIlroy, 1983b). Skunks also experienced convulsions, preceded by a loss of voluntary muscle control and vocalisation (Eastland and Beasom, 1987). Reports describing human cases of fluoroacetate poisoning identify anxiety, irritability, verbosity, agitation, hyperactivity, rapid heart rate, confusion, epigastric pain, headache, nausea and vomiting, faecal incontinence, respiratory distress, hyperaesthesia, muscular twitches, muscular pain, tetanic spasms, cardiac irregularity, gradual loss of alertness leading to coma, epileptiform convulsions, tonic convulsions, periods of flacidity, periods of lucidity between convulsions, and partial paralysis (Gajdusek and Luther, 1950; Peters, 1952; Brockman et al., 1955; McTaggart, 1970; Reigart et al., 1975; Trabes et al., 1983; Chung, 1984; Chi et al., 1996, 1999; Robinson et al., 2002).

6. Carnivores

Chenoweth and Gilman (1946) observed that cats displayed similar signs to pigs and Rhesus macaques so, like these animals, cats were placed into symptomatic Class II. In contrast, poisoned dogs displayed extensive neurological involvement and were placed in Class III, animals in which the main effect of fluoroacetate poisoning is on the nervous system.

The signs that Chenoweth and Gilman (1946) described in poisoned cats include vomiting, salivation, rapid breathing, hyperexcitability, dilation of the pupils, tonic convulsions, and clonic convulsions. Death typically resulted from depression of the respiratory centre but occasionally as a result of ventricular fibrillation. Foss (1948) also carried out experimental poisoning of cats with fluoroacetate observing many of the same signs (retching and vomiting, rapid respiration, dilation of the pupils, and clonic convulsions) as well as incontinence, ataxia, and partial paralysis. In a veterinary case of accidental poisoning in a domestic cat, Gammie (1980) reported vomiting, hyperaesthesia to light and touch, pulmonary congestion, excessive salivation and vocalisation, tremors, dilation of the pupils, exaggerated reflexes, low body temperature, and bradycardia.

Chenoweth and Gilman (1946) found that poisoned dogs displayed hyperexcitability, excessive vocalisation, snapping and biting, salivation, defecation, twitching of facial muscles, nystagmus, tonic convulsions, and convulsions with paddling of the limbs, with periods of lucidity between convulsions. Death resulted from depression of the respiratory centre. Further experiments carried out by Chenoweth and St John (1947) again described vomiting, excessive vocalisation, snapping, and clonic convulsions with death resulting from depression of the respiratory centre. Other authors have reported many of the same signs of poisoning in dogs, describing apprehension, agitation, retching and vomiting, hyperactivity, vocalisation, excessive salivation, incontinence of urine and faeces, dilation of the pupils, tonic convulsions, then clonic convulsions with champing of the jaws and paddling of the limbs (Foss, 1948; Harris, 1975). Poisoned foxes behave similarly, displaying retching, hyperactivity, clonospasm, tail twitching, tetanic spasms, and clonic convulsions with paddling of the limbs (Marks et al., 2000).

A study of the effect of fluoroacetate on a wide range of Australian marsupial carnivores (McIlroy, 1981) describes various signs including vomiting, depression, rapid shallow breathing, trembling, restlessness, hyperactivity, unusual vocalisations, biting, incontinence, excessive salivation, rapid blinking, twitching of facial muscles, nystagmus, ataxia, hypersensitivity to stimuli, tetanic seizures, dilation of the pupils, clonic convulsions with paddling of the limbs, and partial paralysis.

7. Rodents

In their experiments, Chenoweth and Gilman (1946) observed the effects of fluoroacetate on guineapigs (*Cavia porcellus*), hamsters and rats. However, they did not specify which species or breeds of the latter were used. They found that guineapigs displayed neurological involvement similar to that described for the dog, so they placed guineapigs in symptomatic Class III along with dogs. Hamsters and rats displayed signs that Chenoweth and Gilman (1946) regarded as atypical and were given their own category, Class IV, in which there is an atypical response to fluoroacetate poisoning characterised by weakness and extreme bradycardia.

According to Chenoweth and Gilman's (1946) descriptions poisoned guineapigs behaved similarly to dogs, with "long continued convulsions interspersed with a tremorous state". They also reported that guineapigs were hypersensitive to mechanical stimulation. Death in these animals resulted from respiratory depression. Other authors described signs in poisoned guineapigs as including respiratory distress with froth emanating from the nose and mouth, apprehension, hyperexcitability, tonic convulsions, and periods of flaccidity (Quin and Clark, 1947; Foss, 1948).

Chenoweth and Gilman (1946) found that poisoned hamsters and rats became tremorous, hyperexcitable, hypersensitive to mechanical stimulation, had tonic convulsions, displayed abnormal posturing, refused food and water, and either died quickly of respiratory depression or slowly after a period of weakness and extreme bradycardia. Other authors also describe hyperexcitability, and tonic convulsions in rats (Foss, 1948; Hayes et al., 1973; Egekeze and Oehme, 1979). However, Foss (1948) argues that repeated convulsions are common in rats, whereas Chenoweth and Gilman (1946) described them as rare, and in a further contrast to Chenoweth and Gilman's (1946) findings, Foss (1948) describes rats, mice and guineapigs as having identical signs of poisoning. Other authors have also described apprehensive behaviour, depression, abnormal posturing suggestive of abdominal pain, abnormal vocalisations, severe respiratory distress, spasms of the

abdominal muscles, defecation and urination, dilation of the pupils, clonic convulsions, severe convulsions resulting in physical harm, and periods of flaccidity in rats poisoned with fluoroacetate (Foss, 1948; Hayes et al., 1973; Egekeze and Oehme, 1979).

Other studies investigating the effects of fluoroacetate on rodents have used white mice (*Mus musculus*), prairie dogs (*Cynomys ludovicianus*), and a range of Australian native rodents. White mice were described as becoming lethargic, displaying apprehensive behaviour, becoming hyperexcitable, experiencing tetanic spasms, as well as periods of flaccidity and respiratory distress (Quin and Clark, 1947; Foss, 1948; Nwude et al., 1977). Black-tailed prairie dogs developed rapid respiration, hyperactivity, then severe convulsions (Hugghins et al., 1988). Australian native rodents were also described as appearing depressed with abnormal posturing, shivering, ruffled fur, low temperature, hypersensitivity, ataxia, and respiration that was initially rapid but became progressively slower and shallower (McIlroy, 1982b). Some species exhibited unusual vocalisations, hyperactivity, biting, clonic convulsions with paddling of the limbs, ejaculation, and partial paralysis (McIlroy, 1982b).

8. Reptiles and amphibians

Only one amphibian was included in Chenoweth and Gilman's (1946) study, a frog of unspecified species. Chenoweth and Gilman observed that frogs were highly tolerant of fluoroacetate and displayed only neurological involvement (Class II). The signs they describe are convulsions, and paralysis. Australian native reptiles and amphibians are also relatively tolerant of fluoroacetate but display a wide range of signs of poisoning including lethargy, retching, foaming at the mouth, rapid blinking, muscular spasms, and convulsions with paddling of the legs (McIlroy, 1985).

9. Birds

When Chenoweth and Gilman (1946) investigated the effects of fluoroacetate on fowl (*Gallus gallus*) they found that they had persistent convulsions, but died of ventricular fibrillation. In contrast, Quin and Clark (1947) failed to note any signs in poisoned fowl prior to death. The experimental poisoning of common starlings (*Sturnus vulgaris*) (Balcomb et al., 1983) and a range of birds native to Australia and New Zealand (McIlroy, 1984; McIntosh et al., 1966) has been described in detail. Signs of poisoning observed include: depression, prostration, vomiting, abnormal posturing, unusual vocalisations, ruffled feathers, shivering, trembling, excessive salivation, respiratory distress, hypersensitivity to stimuli, ataxia, loss of balance, hyperactivity, grasping and biting, convulsions with paddling of the limbs, severe tetanic seizures, opisthotonos, and partial paralysis.

10. Similarities between species

Overall, the division of fluoroacetate toxicosis into symptomatic categories is problematic. Where the signs/symptoms of fluoroacetate poisoning have been recorded in detail, there are obvious similarities between species. In the early stages of poisoning (following the initial lag-stage during which fluoroacetate is metabolised to fluoroacetate) animals are typically reported as displaying a range of signs including; lethargy, retching and vomiting, trembling, faecal and/or urinary incontinence, unusual vocalisations, hyperactivity, excessive salivation, muscular weakness, uncoordination, hypersensitivity to nervous stimuli, and respiratory distress. Local neurological signs including muscular twitches (often affecting the face e.g. nystagmus, blepharospasm, etc.), and tetanic spasms of the tail and limbs commonly follow. Neurological involvement may then progress to generalised convulsions, initially of a tetanic (tonic) nature, then of a clonic-tonic form, convulsions usually occurring cyclically (often with periods of lucidity in between (Chenoweth and St John, 1947; Foss, 1948; Gajdusek and Luther, 1950; McIlroy, 1982a; Schultz et al., 1982)). Partial paralysis (sometimes lasting for prolonged periods) is also common, especially in animals recovering from sublethal amounts of fluoroacetate (Table 1).

The division of animals into cardiac and neurological symptomatic groups is particularly unsatisfactory as it ignores common neurological signs in the former group (e.g. tremor, myotonic convulsions, muscular weakness, hypersensitivity and partial paralysis).

Table 1
Common signs/symptoms of fluoroacetate poisoning and the groups of animals that they have been reported in

Symptoms	Animals
Lethargy	Eutherian herbivores, marsupial herbivores, omnivores, marsupial carnivores, rodents, reptiles/amphibians, birds (Quin and Clark, 1947; Foss, 1948; Meldrum and Bignell, 1957; Robison, 1970; Hayes et al., 1973; Nwude et al., 1977; McIlroy, 1981, 1982a,b, 1983a,b, 1984, 1985)
Retching/vomiting	Omnivores, humans, eutherian carnivores, marsupial carnivores, reptiles/amphibians, birds (Chenoweth and Gilman, 1946; Chenoweth and St John, 1947; Foss, 1948; Gajdusek and Luther, 1950; McTaggart, 1970; Harris, 1975; McIlroy, 1981, 1983a,b, 1984, 1985; Trabes et al., 1983; Chung, 1984; Chi et al., 1996, 1999; Marks et al., 2000; Robinson et al., 2002)
Trembling/shivering	Marsupial herbivores, omnivores, marsupial carnivores, rodents, birds (Chenoweth and Gilman, 1946; McIlroy, 1981, 1982a,b; Balcomb et al., 1983; McIlroy, 1983b, 1984)
Ataxia/uncoodination	Eutherian herbivores, marsupial herbivores, eutherian carnivores, marsupial carnivores, rodents, birds (Foss, 1948; Meldrum and Bignell, 1957; McIlroy, 1981, 1982a,b, 1984)
Muscular weakness/collapse	Eutherian herbivores, omnivores, marsupial carnivores, rodents (Chenoweth and Gilman, 1946; Foss, 1948; Robison, 1970; McIlroy, 1981, 1982a; Schultz et al., 1982; Eastland and Beasom, 1987)
Faecal and/or urinary incontinence	Eutherian herbivores, marsupial herbivores, omnivores, humans, eutherian carnivores, marsupial carnivores, rodents, birds (Chenoweth and Gilman, 1946; Foss, 1948; Brockman et al., 1955; Harris, 1975; Egekeze and Oehme, 1979; McIlroy, 1981, 1982a; McIlroy, 1984; Schultz et al., 1982; Chi et al., 1996, 1999)
Abnormal vocalizations/verbosity	Eutherian herbivores, marsupial herbivores, omnivores, humans, eutherian carnivores, marsupial carnivores, rodents, birds (Chenoweth and Gilman, 1946; Chenoweth and St John, 1947; Foss, 1948; Meldrum and Bignell, 1957; Harris, 1975; Egekeze and Oehme, 1979; Gammie, 1980; McIlroy, 1981, 1982a,b, 1984; Eastland and Beasom, 1987; Chi et al., 1996)
Hyperactivity/agitation	Eutherian herbivores, omnivores, humans, eutherian carnivores, marsupial carnivores, rodents, birds (Chenoweth and Gilman, 1946; Chenoweth and St John, 1947; Foss, 1948; Harris, 1975; Nwude et al., 1977; Egekeze and Oehme, 1979; McIlroy, 1981, 1982b; McIlroy, 1984; Schultz et al., 1982; Trabes et al., 1983; Hugghins et al., 1988; Chi et al., 1996; Marks et al., 2000; Robinson et al., 2002)
Excessive salivation	Omnivores, humans, eutherian carnivores, marsupial carnivores, birds (Chenoweth and Gilman, 1946; Harris, 1975; Gammie, 1980; McIlroy, 1981, 1984)
Rapid respiratory rate	Eutherian herbivores, marsupial herbivores, eutherian carnivores, marsupial carnivores, rodents, reptiles/amphibians, birds (Chenoweth and Gilman, 1946; Foss, 1948; Egekeze and Oehme, 1979; Gammie, 1980; McIlroy, 1981, 1982a,b, 1984, 1985; Hugghins et al., 1988)
Respiratory distress and/or foaming at the nostrils and mouth	Eutherian herbivores, marsupial herbivores, omnivores, humans, eutherian carnivores, marsupial carnivores, rodents, reptiles/amphibians, birds (Quin and Clark, 1947; Foss, 1948; McIlroy, 1981, 1982a; Schultz et al., 1982; McIlroy, 1983a, 1984, 1985; Chi et al., 1996)
Hypersensitivity	Eutherian herbivores, marsupial herbivores, omnivores, eutherian carnivores, marsupial carnivores, rodents, birds (Chenoweth and Gilman, 1946; Gammie, 1980; McIlroy, 1981, 1982a,b, 1983b, 1984; Schultz et al., 1982)
Muscular twitches	Eutherian herbivores, omnivores, humans, eutherian carnivores, marsupial carnivores, rodents, reptiles/amphibians (Chenoweth and Gilman, 1946; Foss, 1948; Robison, 1970; Egekeze and Oehme, 1979; McIlroy, 1981, 1985; Schultz et al., 1982; Chung, 1984; Marks et al., 2000)
Paresis/paralysis	Eutherian herbivores, omnivores, humans, eutherian carnivores, marsupial carnivores, rodents, reptiles/amphibians, birds (Chenoweth and Gilman, 1946; Foss, 1948; Gajdusek and Luther, 1950; Peters, 1952; McTaggart, 1970; McIlroy, 1981, 1982a,b, 1983a, 1984)
Tetanic (myotonic) seizures	Omnivores, humans, eutherian carnivores, marsupial carnivores, rodents, birds (Chenoweth and Gilman, 1946; Quin and Clark, 1947; Foss, 1948; Gajdusek and Luther, 1950; Brockman et al., 1955; McTaggart, 1970; Hayes et al., 1973; Harris, 1975; McIlroy, 1981, 1984; Schultz et al., 1982; Marks et al., 2000)
Clonic-tonic convulsions (in-place running)	Eutherian herbivores, marsupial herbivores, omnivores, humans, eutherian carnivores, marsupial carnivores, rodents, reptiles/amphibians (Chenoweth and Gilman, 1946; Chenoweth and St John, 1947; Foss, 1948; Gajdusek and Luther, 1950; Brockman et al., 1955; McTaggart, 1970; Robison, 1970; Hayes et al., 1973; Harris, 1975; McIlroy, 1981, 1982a,b, 1985; Trabes et al., 1983; Chung, 1984; Chi et al., 1996; Marks et al., 2000; Robinson et al., 2002)
Convulsions of an unspecified type	Eutherian herbivores, marsupial herbivores, omnivores, rodents, birds (Foss, 1948; Meldrum and Bignell, 1957; Nwude et al., 1977; Egekeze and Oehme, 1979; McIlroy, 1982a, 1983a; Balcomb et al., 1983; Eastland and Beasom, 1987; Hugghins et al., 1988)

It also fails to recognise the neurological basis of signs/symptoms such as retching and vomiting, agitation, verbosity, epigastric pain, incontinence, and excessive salivation. All of which are consistent with over-stimulation of the autonomic nervous system. Foss (1948) proposed that variations in signs observed in animals poisoned with fluoroacetate could be explained by the relative buildup of citrate in the affected tissues (cardiac versus neurological). In fact, over-stimulation of the autonomic nervous system resulting from the increasing metabolic acidosis caused by citrate buildup is a probable cause of several of the more common signs and symptoms of fluoroacetate toxicosis (see above). Later involvement of the CNS as well as cardiac involvement may possibly reflect the differential buildup of citrate in those tissues as suggested by Foss (1948). However, the cardiac response has only been determined for a limited number of animals (Chenoweth and Gilman, 1946) and CNS involvement is clearly widespread, as evidenced by the generality of signs such as ataxia, collapse, hypersensitivity, partial paralysis, tetanic seizures and clonic-tonic convulsions (Table 1).

11. Conclusions

It is misleading to argue that vertebrates can be placed into four categories on the basis of the signs/symptoms that they display when poisoned with fluoroacetate. Animals generally display a high degree of similarity in the response to fluoroacetate intoxication, and neurological involvement is far more common than previously inferred.

References

Balcomb, R., Bowen III, C.A., Williamson, H.O., 1983. Acute and sublethal effects of 1080 on starlings. Bull. Environ. Contam. Toxicol. 31, 692–698.

Booth, L.H., Wickstrom, M.L., 1999. The toxicity of sodium monofluoroacetate (1080) to *Huberia striata* a New Zealand native ant. N. Z. J. Ecol. 23, 161–165.

Brockman, J.L., McDowell, A.V., Leeds, W.G., 1955. Fatal poisoning with sodium fluoroacetate. J. Am. Med. Assoc. 159, 1529–1532.

Chenoweth, M.B., Gilman, A., 1946. Studies on the pharmacology of fluoroacetate. I. Species responses to fluoroacetate. J. Pharmacol. Exp. Therap. 87, 90–103.

Chenoweth, M.B., St John, E.F., 1947. Studies on the pharmacology of fluoroacetate. III. Effects on the central nervous system of dogs and rabbits. J. Pharmacol. Exp. Therap. 90, 76–82.

Chenoweth, M.B., 1949. Monofluoroacetic acid and related compounds. J. Pharmacol. Exp. Therap. 1, 383–424.

Chi, C.H., Chen, K.W., Chan, S.H., Wu, M.H., Huang, J.J., 1996. Clinical presentation and prognostic factors in sodium monofluoroacetate intoxication. J. Toxicol. Clin. Toxicol. 34, 707–712.

Chi, C.H., Lin, T.K., Chen, K.W., 1999. Hemodynamic abnormalities in sodium monofluoroacetate intoxication. Human Exp. Toxicol. 18, 351–353.

Chung, H.M., 1984. Acute renal failure caused by acute monofluoroacetate poisoning. Vet. Human Toxicol. 26 (Suppl. 2), 29–32.

Duin, D., Bernem, D.A., 1968. Oxidation of glucose-1-14C, glucose-6-14C and acetate-1-14C by rat ventricular strips during the inotropic action of fluorocitrate. Life Sci. 5, 1881.

Eastland, W.G., Beasom, S.L., 1987. Acute toxicity of sodium monofluoroacetate to the striped skunk. Bull. Environ. Contam. Toxicol. 38, 934–936.

Egekeze, J.O., Oehme, F.W., 1979. Inorganic and organic fluoride concentrations in tissues after the oral administration of sodium monofluoroacetate (Compound 1080) to rats. Toxicology 15, 43–53.

Fanshier, D.W., Gottwald, L.K., Kun, E., 1964. Studies of specific enzyme inhibitors. VI. Characterisation and mechanism of action of the enzyme inhibitory isomer of monofluorocitrate. J. Biol. Chem. 239, 425–434.

Foss, G.L., 1948. The toxicology and pharmacology of methyl fluoroacetate (MFA) in animals, with some notes on experimental therapy. Brit. J. Pharmacol. 3, 118–127.

Gajdusek, D.C., Luther, G., 1950. Fluoroacetate poisoning: a review and report of a case. Am. J. Dis. Child. 79, 310–320.

Gammie, J., 1980. Sodium fluoroacetate poisoning in a cat. Can. Vet. J. 21, 64.

Harris, W.F., 1975. Clinical toxicities of dogs. Vet. Clin. N. Am. 5, 605–622.

Hayes, F.D., Short, R.D., Gibson, J.E., 1973. Differential toxicity of monochloroacetate, monofluoroacetate and monoiodoacetate in rats. Toxicol. Appl. Pharmacol. 26, 93–102.

Hugghins, E.J., Casper, H.H., Ward, C.D., 1988. Tissue fluoroacetate residues in prairie dogs dosed with low-level sodium monofluoroacetate. J. Assoc. Official Anal. Chem. 71, 579–581.

Marks, C.A., Hackman, C., Busana, F., Gigliotti, F., 2000. Assuring that 1080 toxicosis in the red fox (*Vulpes vulpes*) is humane: fluoroacetic acid (1080) and drug combinations. Wildl. Res. 27, 483–494.

McIlroy, J.C., 1981. The sensitivity of Australian animals to 1080 poison. II. Marsupial and eutherian carnivores. Aust. Wildl. Res. 8, 385–399.

McIlroy, J.C., 1982a. The sensitivity of Australian animals to 1080 poison. III. Marsupial and eutherian herbivores. Aust. Wildl. Res. 9, 487–503.

McIlroy, J.C., 1982b. The sensitivity of Australian animals to 1080 poison. IV. Native and introduced rodents. Aust. Wildl. Res. 9, 505–517.

McIlroy, J.C., 1983a. The sensitivity of Australian animals to 1080 poison. V. The sensitivity of feral pigs, *Sus scrofa*, to 1080 and its implications for poisoning campaigns. Aust. Wildl. Res. 10, 139–148.

McIlroy, J.C., 1983b. The sensitivity of Australian animals to 1080 poison. VI. Bandicoots. Aust. Wildl. Res. 10, 507–512.

McIlroy, J.C., 1984. The sensitivity of Australian animals to 1080 poison. VII. Native and introduced birds. Aust. Wildl. Res. 11, 373–385.

McIlroy, J.C., 1985. The sensitivity of Australian animals to 1080 poison. VIII. Amphibians and reptiles. Aust. Wildl. Res. 12, 113–118.

McIlroy, J.C., 1986. The sensitivity of Australian animals to 1080 poison IX. Comparisons between the major groups of animals, and the potential danger non-target species face from 1080-poisoning campaigns. Aust. Wildl. Res. 13, 39–48.

McIntosh, I.G., Bell, J., Poole, W.S.H., Staples, E.L.J., 1966. The toxicity of sodium monofluoroacetate (1080) to the North Island weka (*Gallirallus australis greyi*). N. Z. J. Sci. 9, 125–128.

McTaggart, D.R., 1970. Poisoning due to sodium fluoroacetate ("1080"). Med. J. Aust. 2, 641–642.

Meldrum, G.K., Bignell, J.T., 1957. The use of sodium fluoroacetate (compound 1080) for the control of the rabbit in Australia. Aust. Vet. J. 33, 186–196.

Notman, P., 1989. A review of invertebrate poisoning by compound 1080. N. Z. Entomol. 12, 67–71.

Nwude, N., Parsons, L.E., Adaudi, A.O., 1977. Acute toxicity of the leaves and extracts of *Dichapetalum barteri* (Engl.) in mice, rabbits and goats. Toxicology 7, 23–29.

Peters, R.S., 1952. Lethal Synthesis. Proc. Roy. Soc. Lond. 139, 142–170.

Quin, J.I., Clark, R., 1947. Studies on the action of potassium monofluoroacetate (CH_2FCOOK) [*Dichapetalum cymosum* (Hook) Engl.] toxin on animals. Onderstepoort J. Vet. Sci. Anim. Ind. 22, 241–246.

Reigart, J.R., Brueggeman, J.L., Keil, J.E., 1975. Sodium fluoroacetate poisoning. Am. J. Dis. Child. 129, 1224–1226.

Robinson, R.F., Griffith, J.R., Wolowich, W.R., Nahata, M.C., 2002. Intoxication with sodium monofluoroacetate (compound 1080). Vet. Human Toxicol. 44, 93–95.

Robison, W.H., 1970. Acute toxicity of sodium monofluoroacetate to cattle. J. Wildl. Manage. 34, 647–648.

Schultz, R.A., Coetzer, J.A., Kellerman, T.S., Naude, T.W., 1982. Observations on the clinical, cardiac and histopathological effects of fluoroacetate in sheep. Onderstepoort J. Vet. Res. 49, 237–245.

Trabes, J., Rason, N., Avrahami, E., 1983. Computed tomography demonstration of brain damage due to acute sodium monofluoroacetate poisoning. J. Toxicol. Clin. Toxicol. 20, 85–92.

Twigg, L.E., 1994. Occurrence of fluoroacetate in Australian plants and tolerance to 1080 in indigenous Australian animals. In: A.A. Seawright, C. Eason (Eds.), Proceedings of the Science Workshop on 1080, Royal Soc. NZ Misc. Series 28.

Twigg, L.E., King, D.R., Bowen, L.H., Wright, G.R., Eason, C.T., 1996a. Fluoroacetate content of some species of the toxic Australian plant genus, *Gastrolobium*, and its environmental persistence. Natural Toxins 4, 122–127.

Twigg, L.E., King, D.R., Bowen, L.H., Wright, G.R., Eason, C.T., 1996b. Fluoroacetate found in *Nemcia spathulata*. Aust. J. Bot. 44, 411–412.

Twigg, L.E., Wright, G.R., Potts, M.D., 1999. Fluoroacetate content of *Gastrolobium brevipes* in Central Australia. Aust. J. Bot. 47, 877–880.

Working Group of the Vertebrate Pests Committee (VPC) 2001. Report to Vertebrate Pests Committee: 1080 policies, practices and procedures, Australia and New Zealand.