

# Biorational Approaches to Flea (Siphonaptera: Pulicidae) Suppression: Present and Future<sup>1</sup>

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**ABSTRACT** Cat fleas (*Ctenocephalides felis felis* [Bouché]) are common pests of the urban environment, both in homes and around the premises. Successful management involves suppression of fleas indoors, outdoors, and on the pet. Alternative control methods for development of integrated management systems may include chemical, biological control, sanitation, mechanical, environmental modification, host animal resistance, semiochemical, and genetic techniques. Because of the close association of pets and flea habitat to humans, both on-animal and environmental chemical use may maximize opportunities for human exposure to pesticides. For adoption, alternative strategies must be easy to use, unobtrusive, and effective.

**KEY WORDS** cat flea, Siphonaptera, Pulicidae, *Ctenocephalides felis felis*, IPM, biorational, IGR, biological control, larvicide

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Cat fleas (*Ctenocephalides felis felis* [Bouché]) are common pests of the urban environment, both in homes and around the premises. Fleas affect the home's occupants by causing itching and irritation. In addition, they produce flea allergy dermatitis in hyperallergic animals and serve as the obligate intermediate host of the dog tapeworm, *Dipylidium caninum* (L.). Their shared intimacy with pet owners makes ectoparasites of companion animals a public health menace (Koehler et al. 1994). Cat fleas can serve as bridges for zoonoses such as murine typhus and plague to move from wildlife into human habitations (Williams et al. 1992). Public health and personal comfort make integrated pest management (IPM) of pests of humans and animals problematic. Successful management involves suppression of fleas indoors, outdoors, and on the pet.

Children and adults hug and pet the companion animal, thereby exposing themselves to substances on their pet. Modes of insecticide application such as dusts, sprays, dips, and shampoos increase applicator exposure (Davis et al. 1992). Environmental treatment necessitates application of insecticides to virtually the entire carpeted area of the home, as carpet is the habitat of the developing flea

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(Byron 1987). The volume and rate of insecticide applied in flea treatments is typically greater than that for any other indoor pest (Dryden & Rust 1994). Consequently, the concern for both human and pet safety is the impetus behind the development of alternative methods of flea suppression.

Development of biorational controls for arthropod pests of companion animals has been limited by three main features. First, this is a niche market, with little economic incentive to develop specific products for pests of companion animals. Second, development of insecticide resistance in fleas has made many traditional insecticides ineffective (WHO 1992). Because the action threshold is so low, treatment for fleas is essentially continuous, with virtually 100% of the population under selection pressure. As only a few products are registered for fleas, and compounds from the same chemical class are often used against several life stages, selection pressure is intense. And third, clientele are demanding, simultaneously, a virtually flea-free environment and the avoidance of "hard" traditional pesticides.

### Chemicals

Historically, flea control has been based on the use of traditional insecticides, including chlorinated hydrocarbons, cyclodienes, organophosphates, carbamates, and pyrethroids for both premise and on-animal treatment. Recent introductions include imidacloprid (Advantage<sup>®</sup>), a nitroguanidine that works by binding to nicotinyl receptor sites on the postsynaptic neuron and thus disrupting the insect nervous system (Moffat 1993). Another new product is fipronil (Frontline<sup>®</sup>), a phenylpyrazole that acts on invertebrate gamma-aminobutyric acid receptors (Postal et al. 1995). Both Advantage<sup>®</sup> and Frontline<sup>®</sup> are formulated as on-animal adulticides.

In the last 2 decades, a major shift has occurred with the introduction of insect growth regulators for flea suppression (Brakke 1988). Products are formulated for animal treatment and environmental application. Juvenile hormone mimics such as methoprene (Moser et al. 1992), fenoxycarb (Marchiondo et al. 1990), and pyriproxyfen (Meola et al. 1996) have been used for suppression of immature flea stages in homes. Those exhibiting photostability, fenoxycarb and pyriproxyfen, also have been registered for outdoor use (Palma & Meola 1990).

**Adulticides.** Adulticides act directly on adult fleas and typically are formulated for rapid knockdown and kill. Their mode of action may target the nervous system or other vital body processes. Adulticides are applied to environmental surfaces where adult fleas will contact them (Koehler et al. 1986).

*Traditional insecticides.* Outdoor flea suppression remains one of the most challenging components of flea control programs, with many registered compounds having low efficacy, and even the most effective ones having limited residual activity (Metzger et al. 1996). Potential developmental sites must be identified and treated with an appropriate rate of insecticide, but then environmental conditions rapidly degrade most compounds.

On-animal products must have several features to be successful. These include ease of use (to ensure owner/user compliance), low mammalian toxicity,

and rapid efficacy against fleas. Treatment of the pet exploits the adult cat flea's dependency on its host, in effect making the host analogous to a "trap crop" (Kissileff 1962).

*Botanical insecticides.* The botanical compounds pyrethrum, sabadilla, and rotenone have been recommended for flea suppression (Bishopp 1921). Limonene (Hink & Fee 1986) and linalool (Hink et al. 1988) have been labelled for flea control. The potential exists for the development of other herbal extracts as pulicides, particularly those with folk-history such as the aptly named fleabane and pulegone from certain plants (Chatterjee et al. 1968, Sudekum et al. 1992, Nicholson 1995). Neem also has been found to be toxic to fleas (Kilonzo 1991).

Interestingly, egg, larval, and adult cat fleas may be killed with dusts containing small amounts of naturally occurring hexa-hydroxyl fragrance oils such as alpha-terpineol, benzyl acetate, benzyl alcohol, eugenol, phenylethyl alcohol, and others (D. A. R., unpublished data). Some of the fragrance substances most active against fleas have high insect specificity, and initial studies have shown that they apparently interfere with the insect octopamine system, resulting in paralysis that mimics the paralysis produced from exposure to pyrethroids. Closely related compounds such as benzyl benzoate, diethyl phthalate, and dipropylene glycol are not active. Some of the active substances are safe for humans, and are presently being used as Food and Drug Administration-approved flavor and odor additives in cosmetics, foods, and air fresheners. Dust diluents and aerosol propellants increase cuticular penetration, greatly enhancing the activity of the fragrance oils against fleas. At 98% RH, as little as 9.7 cc/m<sup>2</sup> of a proprietary calcium carbonate-based dust containing <1% alpha-terpineol (EcoSafe, Inc., Roswell, Georgia) provided 100% kill of adult fleas in deep shag carpeting within 24 h. At 60% RH, only 2.2 cc/m<sup>2</sup> was needed to provide complete kill (D. A. R., unpublished data). Mixtures and analogous fragrance substances probably will be proven to be even more efficacious.

The assumption is that hematophagous arthropods such as fleas, having had less evolutionary pressure to develop strategies for dealing with plant allelochemicals, are more likely to be susceptible to botanical insecticides than are phytophagous pests. However, botanical compounds are not free of toxicity to mammals and nontarget species and may offer no inherent advantage over synthetic pesticides (Hinkle 1995).

**Larvicides.** In general, larvicides act on the principle of suppressing immature fleas before they reach the adult biting-pest stage. We discuss three types of larvicides against cat fleas: insect growth regulators, insect development inhibitors, and borates and other stomach toxicants.

*Insect growth regulators.* Larvicides that mimic the effect of juvenile hormone have included methoprene, fenoxycarb, and pyriproxyfen. Pyriproxyfen, in addition to having activity against immature flea stages, has been demonstrated to produce mortality in fleas exposed as adults, due to histopathological damage to internal tissues (Meola et al. 1996).

The juvenile hormone analogs are active against larval cat fleas and effective in reducing development of larvae to adults (Palma & Meola 1990, Palma et al. 1993, Moser et al. 1992). Presumably this inhibition of adult emergence should

be reflected in fewer fleas infesting the hosts, with on-host numbers decreasing over time due to host grooming and flea population senescence (Silverman et al. 1981).

*Insect developmental inhibitors.* The two insect developmental inhibitors cyromazine and lufenuron have been registered for larval flea suppression. Both are given orally to the host animal, absorbed into the bloodstream, and ingested by feeding fleas. The specific mode of action of cyromazine is not clearly understood, but it appears to disrupt or inhibit ecdysis (Friedel 1986, Shipstone & Mason 1995).

Lufenuron is incorporated into the egg prior to oviposition, so that the affected embryo is unable to break through the chorion and emerge (Hink et al. 1991, Zakson et al. 1992). Larvae feeding on adult flea feces containing lufenuron also are affected, being unable to successfully molt due to the inability to form a new exoskeleton (Zakson et al. 1992). Lufenuron-contaminated flea feces thus serve as a bait for larval fleas. Other chitin synthesis inhibitors such as alsystin and diflubenzuron (el-Gazzar et al. 1988) have shown promise for indoor and outdoor uses because of their environmental stability and activity against larval fleas (Henderson & Foil 1993).

Development of insect growth regulators and other physiological mimics is a promising direction for biorational strategies against ectoparasites (el-Gazzar et al. 1986, Spindler-Barth 1992). Because they do not affect adult flea populations but function by reducing environmental infestation and subsequent host reinfestation, prophylactic insect growth regulator applications must be made prior to buildup in flea populations. Because of their photostability and prolonged residual efficacy, some of the insect growth regulators and insect development inhibitors such as pyriproxyfen and diflubenzuron may prove useful for treating outdoor infestations (Palma & Meola 1990, Henderson & Foil 1993). Insect growth regulators are active at low rates and have prolonged residual lives (Hinkle et al. 1995a, Kawada & Hirano 1996), so their use actually reduces the environmental insecticide load (Wright 1976).

*Borates and stomach toxicants.* Borate products also have been demonstrated to be effective larvicides at low rates (Hinkle et al. 1995b). They have additional benefits of long residual efficacy and low mammalian toxicity. Applications of 5% and 10% disodium octaborate solutions with a standard rental carpet cleaning machine to carpets provided >90% kill of larvae for at least 56 d (Rust & Reiersen, unpublished data). Applied in such a way as to contaminate the flea larval food, borates serve as a type of poison bait; formulated in a food matrix, the rate of toxicant could probably be decreased (Klotz et al. 1994).

Other compounds may be similarly used as larval toxicants. Although larval rearing media treated with 2%-5% sodium bicarbonate was not toxic to flea larvae, media containing 2%-5% calcium carbonate killed 85%-88% of larvae (Rust & Reiersen, unpublished data).

### Biological Control

Biological control components are limited for fleas. Biological control is the antithesis of "eradication" because it assumes that some portion of the pest

population will be left to maintain the beneficial population. Most people are willing to accept this concept and practice in agricultural situations, but not in their own homes. In addition, the development of application technology may be even more challenging than finding possible biological control agents.

Biological control of fleas is problematical in that most of the effective pathogens of fleas also are pathogens of humans. For instance, the plague bacillus, *Yersinia pestis* (Yersin), is eventually fatal to virtually all infected fleas. However, the feeding activity of the infected flea prior to its death typically results in further propagation of the infection in mammalian hosts. Development of dog tapeworm cysticercoids can produce >90% mortality in infected fleas (Chen 1934, Marshall 1967). However, in these cases, the attempted solution with biological control is actually worse than the problem.

Fleas do have the added advantage of virtually assured indirect vertical transmission, in that a major portion of the larval diet is the excrement of the adult flea. Thus, infectious agents acquired by the adult will likely be passed along to the developing larvae. However, as the adult flea feeds only on vertebrate blood, there is little chance for infection other than via the host—either pets or humans.

Beard (1988) surveyed potential biological control agents for fleas and summarized the disappointing results by saying, "Biological control is in its infancy with respect to pest management of fleas." Of the possible infectious agents he identified, all appeared to have limited potential as pathogens. Parasitized hosts survived heavy infections and the most frequently observed microorganisms produced heavy infections with no apparent pathogenic effects (Beaucornu & Deunff 1976). Most investigators looking for potential parasites and pathogens, including protozoa and bacteria (Beard et al. 1990), have found only marginally harmful symbionts. No insect-pathogenic viruses have been reported from fleas (Beard 1988).

Other than *Bacillus thuringiensis* Berliner (*Bt*), few of the biological control agents observed have produced high rates of mortality in fleas (Castillo 1980). Although *Bt* parasporal crystals were not found to be toxic, the beta exotoxin produced both developmental abnormalities and mortality (Maciejewska et al. 1988). Some *Bt* products have been patented for other ectoparasites (Payne & Hinkle 1993), but development of effective delivery systems remains challenging.

Host grooming is the most significant mortality factor for adult fleas on the host, with most being removed by the animal within a week (Wade & Georgi 1988). Cats were found to vary in their grooming efficiencies, with poor groomers removing only 4.1% of their flea load per day whereas better groomers removed 17.6% (Hinkle 1992).

Generalized predators such as ants (Fox & Garcia-Moll 1961) and beetles (Fox & Bayona 1968), can have a significant impact on larval flea numbers. As with any on-host pest, there is little opportunity for establishing populations of beneficial arthropods to serve as either parasites, predators, or competitors of the ectoparasites. In general, any arthropod is objectionable on companion animals.

The only known parasitoid of any flea was found parasitizing squirrel fleas in the family Ceratophyllidae (Waterston 1929). The cryptic habits of

immature fleas, particularly pupae in the silken cocoon, reduces their susceptibility to arthropod invasion (Silverman & Appel 1984).

The singular biocontrol option currently marketed for flea control is the nematode *Steinernema carpocapsae* Weiser (Manweiler 1994). Although usage requirements (substrate, temperature, humidity) are restrictive, these parasitic nematodes are effective against the larval and pupal stages in specific outdoor settings (Silverman 1981, Henderson et al. 1995).

### Sanitation

Sanitation is helpful in removing flea eggs before they hatch and in reducing the food available to developing larvae (Robinson 1995). The cleaning action of a standard rental carpet cleaning machine was shown to be inadequate to remove all larval rearing media from carpets and to prevent larval development (Rust & Reiersen, unpublished data). Although vacuuming may remove >90% of flea eggs in carpet, only 15%-27% of larvae are extracted via this method (Byron 1987). Additionally, cleaning pet bedding helps prevent and eliminate infestations because off-host stages are concentrated around areas where pets spend large portions of time (Kern 1993). Ewing (1929) recognized the significance of flea development in pet bedding, saying "if dogs or cats are allowed to sleep in the house, they should be given a mat or rug to lie upon. This mat or rug should be regularly taken out and shaken and left for a few hours in the sun."

### Mechanical

One type of mechanical control includes keeping the animal isolated from a chance of infestation. This method may work with cats that can be confined indoors all the time, but it does not work well with pets that occasionally are allowed outdoors, even for brief intervals. The catholic taste in hosts exhibited by *C. felis* means that virtually any mammal venturing through the property may provide flea contamination to be acquired by a passing pet (Rust & Dryden 1997). Domestic pets often pick up ectoparasites from wild or feral animals, as well, amplifying the opportunity to pass along infections such as bubonic plague, murine typhus, and cat scratch fever. Animals that roam have opportunities to acquire and introduce into the home environment a variety of disease organisms. Thus, exclusion of wild and feral animals from property occupied by pets reduces the opportunity for transmission of flea infestations and their associated diseases.

Traps are physical or mechanical means of eliminating fleas. The concept of a lighted candle in a bowl of soapy water being used to lure in fleas and drown them is ancient (Gaaboub & Abu-Hashish 1974) but has been updated and made more sophisticated by blinking a light and optimizing the wavelength of light used (Dryden & Broce 1993).

Silica gel and diatomaceous earth are reportedly effective larvicides, resulting in lethal desiccation by adsorbing or abrading the protective epicuticular layer (Ebeling 1961). Insects exposed to these dusts lose body water faster than it can be replaced. This water loss is particularly critical for

flea larvae that require high humidities for development (Silverman et al. 1981). However, effectiveness diminishes at high humidity because of the low drying property (i.e., low saturation deficit) of air at high humidities.

Flea combs can be used to mechanically remove adult fleas from the animal's coat; however, their use requires time and effort and is limited by the animal's temperament and haircoat (Olkowski et al. 1991, Kuepper 1995). It is widely recognized that combing removes only a small percentage of the fleas on an animal. Infestation of hosts with known numbers of fleas and combing within 1 h of placement on the animal results in removal of <25%-30% of the original population (Kwochka 1987). Even with intensive combing under circumstances where the number of fleas was known, only 94% of the fleas were recovered from the animal (Dryden 1989).

### Environmental Modification

Alteration of the habitat can make the environment inhospitable such that it cannot support larval survival. High temperature and low humidity are significant mortality factors, especially for immature flea stages (Silverman et al. 1981, Silverman & Rust 1983), so landscape modifications that expose potential developmental sites to drying will reduce survival.

Salt has historically been used as a "siccative" or desiccant in areas where immature fleas develop, by scattering salt on the area dry (Metcalf & Flint 1939) or then wetting it down thoroughly (Bishopp 1921, Furman 1971). Near the coast, soil around runways and kennels was treated with seawater (Ewing 1929).

Flooding can be used not only to drown larvae but also to dissolve the adult fecal material that serves as larval food (Kern 1993). Soil moisture >30% increased cat flea larval mortality to 90% (Silverman & Rust 1983).

### Host Resistance

Host resistance may be either physiological or behavioral (Chandy & Prasad 1987). Physiological resistance may be either inherent or induced. Some hosts have been found to be less supportive of flea development than others. However, it is not known if such differences are due to physiological factors, genetic predisposition, or behavioral factors. Some hosts are better groomers than others (Silverman et al. 1981). Most people do not select their pets based on whether or not the animal can support fleas. In fact, flea-allergic animals exhibit intensified grooming efforts making it more difficult to find fleas on symptomatic animals (Kissileff 1962), and the intense grooming exhibited by some animals is a quality that makes them hyperactive and unaffectionate (Hart 1992, Dryden & Rust 1994). While devoting attention to scratching fleas, a dog or cat is less involved in interactions with the owner.

Physiological host resistance may be due to such attributes as skin pH and blood constituents, or to morphological features such as skin thickness, sebum production, and density of hair coat. Genetic engineering may be used to produce breeds that do not support fleas, as by preventing feeding, reducing viability, or lowering fecundity (Muller & Brem 1994).

Immunologic concepts are being explored for fleas (Opdebeeck & Slacek 1993, Heath et al. 1994). Although a flea would still have to feed on an immunized host, theoretically the subsequent reaction would either result in flea mortality or reduce its fitness, perhaps by lowering its reproductive capacity (Heath et al. 1994). The immunology of reactions to flea antigen is poorly understood. Flea bites typically produce severe urticaria, often leading to frenzied scratching and self-induced alopecia and excoriation. Attempts at inducing host immunity would necessitate isolation of the allergenic fraction to prevent such severe side effects.

### Semiochemicals

Pheromones and other natural products might be used to alter flea behavior to make them less objectionable, as feeding deterrents, mating confusants, or by blocking host location by interfering with chemoreceptors (Slifer 1980). Repellents might be developed to prevent adults from either finding a host or entering a treated area. A better understanding of flea visual and chemical perception is needed before this can be optimally exploited (Benton & Yee 1965).

### Genetic Control

As with any blood-sucking arthropod, the presence of the pest is sufficient to be objectionable. So it is difficult to introduce genetic characters because the modified individuals are as undesirable as the natural ones.

### Summary

Dryden & Rust (1994) and Rust & Dryden (1997) have provided reviews of current control strategies for fleas, both on the host and in the environment. Overwhelmingly, these tactics are based on insecticides. Development of biorational strategies for suppression of fleas is in its infancy and additional research is needed to better understand the pest and to identify potential points of attack. The following are some obvious gaps in current knowledge:

- Understanding of host-ectoparasite interactions (including host-seeking behaviors);
- Vulnerabilities of the pre-emerged adult within the cocoon;
- Triggers and methods of adult flea emergence;
- Role of semiochemicals, pheromones, and other behavioral chemicals affecting host location, mating, and larval food location;
- Determination of susceptible stages in the life cycle;
- Investigation of flea ecology in outdoor settings, including microhabitats and use of alternative hosts;
- Method of flea overwintering;
- Delivery systems for insecticides; and
- Techniques for population monitoring.

Action thresholds for fleas extend beyond economic injury or even aesthetic injury to include "comfort level." Pet owners have their own internal (and variable) tolerance for what they think they and their pet should be exposed to. An animal that is being tormented by fleas does not perform well and may exhibit behavioral problems. In the show ring, an insect-induced welt or coat discoloration caused by insect feeding can be a major detraction. Arthropod-induced appearance defects such as depilation, hyperkeratosis, and depigmentation are significant detriments for show animals and family pets. Flea allergy dermatitis in cats and dogs is sufficiently distressing to some owners that they have the animal euthanized to alleviate the suffering (Fenster 1985).

Monitoring is one of the challenges of developing an effective flea suppression program. Typically, evaluation of the program is based on the homeowner's perceptions, but more objective assessment methods are needed. The "white sock" technique involves the investigator walking through an area wearing knee-high white socks and counting adult fleas clinging to them; this monitoring technique has been used to assess the numbers of adult fleas in homes (Osbrink et al. 1986). Light traps and glue boards may provide the pest control operator with a means of determining extent of control obtained (Dryden & Broce 1993). Hand-held vacuum cleaners have been used for sampling and modifications of this technique could be used for household monitoring (Osbrink et al. 1986).

The factors that make development of alternative pest management strategies for pests of companion animals most desirable are the same factors that make it most challenging. The intimacy of the environment, with pet-owners spending time in close proximity with their animals, exposes humans to both the pest and the chemicals used to treat for it. Clientele are demanding nonchemical alternatives and insecticide resistance is rendering current pesticides ineffective.

Currently, IPM programs for control of arthropod pests of companion animals are restricted by the limited availability of usable components. There is a tremendous need for research into basic biology and behavior of the pest, coupled with discovery and development of alternative strategies, including novel insecticides and innovative delivery systems, that might be employed in an integrated system.

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