Biorational Approaches to Flea (Siphonaptera: Pulicidae) Suppression: Present and Future

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ABSTRACT
Cat fleas (Ctenocephalides felis felis [Bouchard]) 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 strategies 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, bioregional, IGR, biological control, larvicide

Cat fleas (Ctenocephalides felis felis [Bouchard]) 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 hypersensitive animals and serve as the obligate intermediate host of the dog tapeworm, Dipylidium caninum (L.). Their shared intimacy with pet owners make cats parasites of companion animals a public health menace (Kochler et al. 1984). Cat fleas can serve as bridges for aconias such as scrums 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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and rapid efficacy against fleas. Treatment of the pet exploits the adult cat's fleas' dependency on its host, in effect making the host analogous to a "trap crop" (Kissling 1982).

**Botanical insecticides.** The botanical compounds pyrethrum, abamectin, and rotenone have been recommended for flea suppression (Bishop 1921). Limonen (Hink & Foe 1980) and fimalol (Hink et al. 1980) have been labelled for flea control. The potential exists for the development of other herbal extracts as pesticides, particularly those with folk-history such as the aptly named "pleurocane and furene from certain plants" (Chatterjee et al. 1968, Sudakom et al. 1992, Nicholson 1995). Neem has also been found to be toxic to fleas (Kilmarnock 1991).

Interestingly, egg, larval, and adult cat fleas may be killed with dusts containing small amounts of naturally occurring hexa-hydroxy culembols and pyrethrins, such as alpha-terpinene, benzyl acetate, benzyl alcohol, eugenol, phenethyl 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 pyrethrins. 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 diluted in aerosol propellants increase cuticular penetration, greatly enhancing the activity of the fragrance oils against fleas. At 98% RH, as little as 0.7 cm² of a proprietary calcium carbonate-based dust containing 1% alpha-terpinene (EcoSafe, Inc., Roswell, Georgia) provided 100% kill of adult fleas in deep shag carpeting within 2 h. At 60% RH, only 2.2 cm² 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 hematozoan 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 (Kilmarnock 1995).

**Larvicides.** In general, larvicides act on the principle of suppressing immature fleas before they reach the adult biting-stage. We discuss three types of larvicides against cat fleas: insect growth regulators, insect development inhibitors, and larvetates 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 (Meeh et al. 1980). The juvenile hormone analogs are active against larval cat fleas and effective in reducing development of larvae to adults (Palma & Meeh 1990, Palma et al. 1990, Meeh 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 semiconce (Silveman et al. 1991).

**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 1990).

Lufenuron is incorporated into the egg prior to oviposition, so that the affected embryos are unable to break through the chorion and emerge (Hink et al. 1991, Saksou 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 (Saksou et al. 1992). Lufenuron-contaminated flea feces thus serve as a bank for larval fleas. Other chitin synthesis inhibitors such as alphas and diflubenzuron (de Gerazza et al. 1988) have shown promise for indoor and outdoor use 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 biocidal strategies against ectoparasites (de Gerazza 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 & Mesia 1990, Henderson & Foil 1993). Insect growth regulators are active at low rates and have prolonged residual lives (Hinkle et al. 1995b, Kweada & Hirasoe 1996), so their use actually reduces the environmental insecticide load (Wright 1976).

**Borate and stomach toxicants.** Borate products also have been demonstrated to be effective larvicides at low rates (Hinkle et al. 1986b). They have additional benefits of low residual efficacy and low mammalian toxicity. Applications of 5% and 10% diiodooctaborate solutions with a standard carpet cleaning machine to carpets provided >90% kill of larvae for at least 8 d (Rust & Reerson, 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 toxinant could probably be decreased (Rust & Reerson, unpublished data).

**Biological Control**

Biological control components are limited for fleas. Biological control is the antibiosis of "eradiication" 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 problematic in that most of the effective pathogens of fleas are also 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 1954, Marshall 1997). 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 summarised 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. Parasitised hosts survived heavy infections and the most frequently observed microorganisms produced heavy infections with no apparent pathogenic effects (Beaurenurs & Deoff 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 (Maciojevics et al. 1988). Some Bt products have been patented for other ectoparasites (Payne & Hitch 1983), 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% of their flea load per day whereas better groomers removed 17.6% (Hinkle 1992).

Generalised predators such as ants (Fox & Garcia-Moll 1981) and beetles (Fox & Baynes 1980) 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 parasite infected of any flea was found parasitising squirred 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 1980). 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 & Reierman, unpublished data). Although vacuuming may remove >99% 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 cathartic 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 ream 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 & Abo-Hasshish 1974) but has been updated and made more sophisticated by blinking a light and optimizing the wavelength of light used (Dryden & Croce 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. 1983). 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 (Gilkeson et al. 1991, Koeppe 1990). 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 <5%-10% of the original population (Kovchik 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 1988).

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. Soil has historically been used as a "seducative" or "deoxidator" in areas where immature fleas develop, by scattering salt on the area dry (Metcalf & Flint 1939) or then wetting it down thoroughly (Bishop 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 1967). 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 (Kosial 1992), 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 (Möller & 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. Fleas bite typically produce severe urticaria, often leading to frenzied scratching and self-induced alveolus and excoration. Attempts at inducing host immunity would necessitate isolation of the allergenic fraction to prevent such severe side effects.

**Semiocemicals**

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 (Sitter 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 1985).

**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 biocural 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-ecopravate interactions (including host-seeking behaviors);
- Vulnerabilities of the pre-emerged adult within the cocoon;
- Triggers and methods of adult flea emergence;
- Role of semiocemicals, pheromones, and other behavioral chemicals affecting host location, questing, 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.

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**References Cited**


