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The Action of Insecticides*

by

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Definitions

INSECTICIDES are chemicals which kill insects. Repellents drive them away and attractants lure them to their doom. Other chemicals, the chemosterilants, interfere with their reproduction.

In order to do their worst insecticides have naturally to first enter the body of the insect. There are three modes of entry.

Insecticides which enter through the outer covering or integument of the insect, or through the egg shell, are called contact insecticides. Other insecticides enter by way of the mouth and gut, and are called stomach poisons. The third type are the fumigant insecticides which enter through the little apertures through which the insect breathes, the spiracles, into the ramifying system of breathing tubes or tracheae. The tracheae pipe oxygen directly to the individual cells of the insect body.

This demarcation of insecticides into three types is by no means clear-cut, because for example many stomach poisons have a slow action even on contact, and conversely most contact insecticides are poisonous if swallowed. If contact or stomach poisons are volatile they may also function as fumigants.

The Cuticle and Contact Insecticides

Insects, being basically terrestrial animals, need protection from water loss. This protection is afforded by the cuticle, which is really a hardened secretion of the single-cell epithelium covering the body. Apart from covering the body surface the cuticle also enters in at the mouth and anus, leaving only the mid-section of the alimentary canal, or mid-gut, permeable to water. The tracheal tubes also, at least for some distance inward from the spiracles, are lined with cuticle.

The cuticle is hydrophobic because it is impregnated with fatty or lipoid materials. The thin surface layer of the cuticle, or the epicuticle, in particular incorporates a large amount of lipoid or wax. Water does not therefore easily pass out of the body of the insect. Also water falling on the cuticle does not

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enter or block the spiracles, because it gathers into droplets and rolls off, as it does from the proverbial duck's back. This is true as well of aqueous solutions and suspensions of insecticides which have the same high surface tension (up to about 76 dynes per cm.).

The cuticle is at the same time lipophilic. Thus the epicuticle readily admits chemicals which are soluble in lipid solvents. Aqueous sprays are of little use. To get through the cuticular defences one could apply oils of high solubility and low volatility and viscosity. The two main types of oil used are obtained from the distillation products of coal tar and crude petroleum (" tar oils " and " petroleum oils "). Fat solvents may also be used, for example ether or chloroform.

In fact mineral oils and also aqueous solutions of wetting agents like soap, which have a surface tension about one-half that of water, enter through the spiracles into the tracheal system.

Another method for winning through the cuticle is to use inert dusts which abrade off the fat layer and allow the insecticide to enter. Removal of the waterproofing alone is enough to kill the insect because it leads to desiccation, and inert dusts like activated charcoal, alumina, siliceous minerals, etc. have been used in insect control.

The bulk of the cuticle is formed of an inner endocuticle, which is moist and hardly constitutes a barrier to insecticides ; and an outer exocuticle which is tanned and hardened (sclerotised) and might be reasonably expected to offer a sizeable impediment to penetration. However there is evidence that cuticle thickness and sclerotisation are not in fact related to the degree of toxicity of contact insecticides.

A major constituent of insect cuticles is chitin, and DDT is remarkable in that in addition to being fat-soluble it has a strong affinity for chitin. Thus chitin can absorb DDT from a suspension of DDT in water.

Presentation of Contact Insecticides

The presentation of contact insecticides may be made in two ways.

If an immediate kill or " knock down " is required, that is if the insecticide is to act as an eradicant, air-borne particles or droplets are dispersed as mist, aerosol or smoke.

If a residual, long-term insecticidal action is required a surface deposit is made. These are protectant insecticides which control future infestations as well. Thus organochlorines may remain effective for months. DDT is applied to walls, etc. to function as such a protectant — and incidentally kills any insect at all that happens to alight on it, thereby serving to dislocate the ecosytem which the building represents.

The Gut and Stomach Poisons

Material within the alimentary canal of an animal is not within the body at all. It needs to be taken in or absorbed through the wall of the gut. In insects this absorption can take place only through the wall of the mid-gut, which is just one cell thick. As we saw, the fore-gut and hind-gut are lined with intuckings of the cuticle.

Before an insecticide can be absorbed in the mid-gut it needs to be ingested. A problem in the control of the mole rat, which is a pest of our rice crops, is that the rat quickly develops bait-shyness ; it refuses to eat the rodenticide. Fortunately insects are not as finicky. Benzene hexachloride (BHC) which has a strong odour to human beings is no repellent to honey bees for example. However some insects may avoid ingesting insecticides, either at all or in sufficient quantities, because of their off-putting smell or taste. This then is one barrier to be overcome in getting a chemical into the insect's system.

As in ourselves, vomitting can be used as a defence mechanism by insects. This may be overcome by mixing digestive sedatives with stomach poisons ; thus, bismuth subcarbonate with lead arsenate.

The more soluble arsenicals may induce diarrhoea, and therefore their passage through the gut may be too rapid for adequate absorption.

Insecticides having large molecules may not enter the mid-gut cells, or may not penetrate the peritrophic membrane which serves as a sausage-skin to the food in the mid-gut. Some insects may de-fuse stomach poisons within the gut or in the body tissues, perhaps by hydrolysis. The insect excretory organs, the Malpighian tubules, in some cases probably eliminate absorbed poisons before they can cause much damage.

There is no question that before an efficacious insecticide can be selected, as much as possible must be learned of the biology and physiology of the pest species. For instance, before choosing a stomach poison it is necessary to know the pH obtaining within the gut. Inorganic stomach poisons are presented in their most insoluble guise in order to prevent washing off by rain, and to avoid their poisoning plants, but once in the gut of the insect they must go into aqueous solution before they can be absorbed. Different arsenates, for example, have varying degrees of solubility in fluids of different pH ; and in order to decide which arsenate to use the gut pH must be known.

Again, pH may affect the degree of dissociation of the insecticide, and it is known that dissociated arsenical ions are scarcely absorbed, while undissociated arsenical molecules are much more readily absorbed.

Presentation of Stomach Poisons

Stomach poisons are presented mixed with the normal food or in artificial baits. In the case of insects which chew solid food, or lap up exposed liquid food, it is a simple matter to spray or dust insecticide powders onto the food plant (as for caterpillars or beetles) or into the life medium (against mosquito larvae).

The problem is more difficult in the case of insects which pierce the outer covering of a host animal or plant, and suck out the blood or sap. In order to use stomach poisons against these insects, it is necessary to put the poison into the blood, or sap. Such insecticides are called systemics, and are mostly organophosphorus compounds.

Plant systemics are applied to the roots (soil applications) or to the foliage, and are absorbed and carried within the plant in the sap. Systemics used as seed-dressings make seedlings resistant to aphid attack, for example. Insecticides used in this way are safe from modification by the elements, although they may be changed by the plant itself — either into innocuity, or into an even more toxic form.

Animal systemics naturally need to have a low toxicity to mammals, and a few organophosphorus compounds like coumaphos are used. Livestock, and the milk and meat they give, have to be safe from poisoning. Animal systemics are given by mouth, injected, or applied externally.

Fumigant Insecticides

Fumigants are useful in getting rid of pests quickly from enclosed situations. One of the drawbacks about fumigants is that they are usually not residual and reinfestation can occur. (However recently residual fumigants like dichlorvos, having a low volatility, have been developed.) Another drawback is that the more useful fumigants (hydrogen cyanide, carbon disulphide, methyl bromide, phosphine) are very poisonous to human beings as well.

Fumigants find application in the removal of pests from stored bulk foods (seed or grain), and from furs and fabrics. They are also used against pests of glasshouse crops, and for pests in otherwise inaccessible places and in the soil.

The spiracles of insects are opened or closed by action of the insect's nervous system. When the body tissues are acid (if there is too much carbon dioxide or too little oxygen), the spiracles open — obviously to take in more oxygen from the atmosphere. Thus fumigation is best done at reduced pressures (the oxygen tension is then low), or with gas mixtures containing carbon dioxide.

The Metabolic Effects of Insecticides

Many insecticides accomplish their task by interfering with the body's enzymes.

In the cytoplasm of all cells, glucose and other sugars which have a 6-carbon chain are broken down through a series of intermediates to pyruvate, which has a 3-carbon chain. This gives energy which is stored as adenosine triphosphate (ATP). Since the process occurs in the absence of free oxygen, it is called anaerobic glycolysis.

Pyruvate then moves into the mitochondria of the cell, where it enters the tricarboxylic acid cycle (the TCA cycle) as citrate. Citrate passes through a cycle of intermediates in which the carbons and hydrogens of the acetyl group are oxidised to carbon dioxide and water, in the presence of free oxygen. This is called oxidative phosphorylation. Energy or ATP is once more a by-product.

Methyl bromide, arsenicals, and lead and mercury, block the working of triosephosphate dehydrogenase, one of the enzymes in the glycolytic sequence.

Cyanide blocks cytochrome a_3, which in the process of oxidative phosphorylation makes the final transfer of hydrogen ions peeled off TCA cycle intermediates to molecular oxygen to give water. Cyanide is therefore extremely poisonous to all animals.

Dinitrophenol insecticides like dinitro-ortho-cresol are ' uncoupling agents ' of oxidative phosphorylation. They cause energy to be wasted, and prevent it from flowing into the build-up of ATP molecules. Oxidation is uncoupled from phosphorylation. It is said that dinitrophenols cause uncoupling at the point where α-ketoglutarate is oxidised, by introducing inorganic phosphate into the TCA cycle.

Rotenone blocks the enzyme glutamate dehydrogenase which is responsible for converting glutamate into α-oxoglutarate- one of the intermediates in the TCA cycle.

DDT and some other organochlorines or chlorinated hydrocarbons are also thought to inhibit some of the oxidative enzymes, but typically DDT, etc. overstimulate the nervous system and finally cause paralysis. Organochlorines being hydrophobic probably enter into the lipoprotein membranes in the nerve tissue, associate with the lipids there, and interfere with ion movement across the membrane ; ion transfer is necessary for the transmission of nerve impulses. DDT also brings on some effects which are generally seen in insects during starvation ; namely, an increase in blood amino acids, and a decrease in carbohydrate reserves. Another effect of DDT (given by pyrethrins and a particular organophosphorus insecticide as well) is to cause the nervous system to put out a toxin which interferes with nerve co-ordination.

Other organochlorine insecticides like gamma-BHC, and the cyclodienes (chlordane, heptachlor, etc.), affect the nervous system — but centrally, not peripherally in the sensory nerves as does DDT. Cyclodenes like endrin and dieldrin apparently disrupt the process of excretion n the Malpghan tubules.

Electrical nerve impulses pass from nerve cell to nerve cell, and from nevre cell to muscle cell, in the form of a chemical substance, such as acetylcholine (ACh), secreted by the termination of the elongated nerve cells. ACh is quickly hydrolysed by the enzyme acetylcholinesterase (AChase), which is present near the nerve cells. This removal of ACh is necessary to keep the junction inactive, until the next message comes along.

Organophosphorus insecticides bring about a change in the nature of AChase by phosphorylation, and ACh is therefore able to bank up resulting in haphazard nervous activity, and in the end paralysis and death. (DDT also causes ACh to accumulate, but not by interfering with the working of AChase.)

Certain organophosphorus insecticides are not very toxic to mammals. One of the reasons is that perhaps mammalian tissues cannot convert organophosphorus compounds like parathion, malathion and schradan into Achase destroyers, as can the insect gut and fat body by oxidation. However malathion does disrupt the oxidation of pyruvate and citrate ; and in general organophosphorus insecticides may block other biochemical processes as well.

The third group of present-day insecticides, the carbamates, act as competitive inhibitors. A section of the carbamate molecule resembles ACh, and some of the enzyme AChase attaches to the 'wrong' substrate, carbamate, which hydrolyses much slower than the normal substrate, ACh. AChase does not therefore dismantle the ACh fast enough to prevent the dangerous consequences of its accumulation.

Resistance to Insecticides

In an insect population some individuals may be resistant to a particular insecticide. This resistance may be due to peculiarities of structure which interfere with insecticide entry ; or to biochemical processes which render the insecticides innocuous; or perhaps even to behavioural avoidance of insecticides.

Repeated use of an insecticide will eliminate the 'normal' indivduals, and only the resistant or tolerant will survive. If the characteristics giving resistance are inherited, a completely resistant population will emerge sooner or later. The process is really a selection of genetical tendencies already present in the population, and is exactly like the selective process which leads to the emergence of new species and subspecies by factors in nature.

Resistance developed in response to a particular insecticide may also hold for other chemicals of the same type (cross-resistance). Insects resistant to DDT are usually also resistant to methoxychlor (but not necessarily to other organochlorines).

Mercifully resistance is less widespread than it might be. One reason is possibly that resistant individuals, which result from insectcde use, breed with 'normal' individuals from adjacent areas, where the insecticide has not been used. Thus resistance is found more often in relatively immobile insects like coccids, in which this sort of inter-breeding is not possible.

The various reasons for resistance to DDT include a changed permeability of the cuticle ; better putting away of the absorbed poison in places in the insect's system where it cannot do much harm ; and most notably an enormous increase in the amount of an enzyme, DDT dehydrochlornase, present only in traces in normal insects, which changes DDT (which everyone nowadays knows to be dichloro diphenyl trichloroethane) to the less toxic dichloro diphenyl dichloroethylene (DDE).

DDT-resistant insects may however be controlled if the DDT is mixed with usually harmless DDT-like chemicals to act as so-called synergists. These synergists to some extent elbow out the DDT and combine with the dehydrochlorinase themselves, and so keep the offending enzyme occupied.

Toxicity of Insecticides to Other Animals

It has to be realised that, generally speaking, insecticides are toxic to all animals. Insecticides seem to be specific for insects because they happen to have ease of entry into the insect's system ; the mammalian integument for instance is a much more effective barrier than the insect integument to, say, DDT.

However there are a few differences in the way insecticides are dealt with inside vertebrates and insects. Thus, vertebrate tissue has a mechanism, not found in insects, which oxidises DDT to comparatively non-toxic dichloro diphenyl acetic acid. Again, pyrethrum has perhaps the lowest mammalian toxicity because it is quickly degraded in the intestine and tissues of mammals. Mammalian tissues have greater carboxyesterase activity than insect tissues, and some organophosphorus esters like malathion are broken down and easily rendered ineffective in mammals. In insects they remain stable and toxic.

It would appear that much of the divergence, in general opinion, as to whether the use of insecticides is dangerous or not to human beings stems from a confusion between acute poisoning and chronic poisoning. We ought not to be worried so much about occasional cases of acute poisoning, resulting from accidental or deliberate ingestion of insecticides. All our modern aids to better living are open to this sort of misuse.

What ought to concern us much more are the dangers that might result from continual exposure to small doses of people who actually work with insecticides, or who handle products treated with insecticides. And of course we all ingest or take in small quantities of these poisons all the time.

It has been authoritatively suggested that people who spray insecticides should use rubber gloves when handling them ; wear protective clothing during the spraying ; and change their clothes and bathe after the entire operation. Of course we Ceylonese are very prone to bathing every day, but surely many insecticide sprayers in this country work bare-bodied and without benefit of gloves. What is going to happen to them, and to their children's children ?