THE ACTION OF METALDEHYDE ON THE SLUG *AGRIOLIMAX RETICULATUS* (MÜLLER)

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(With 1 Text-figure)

Metaldehyde both as powder and in solution can act on slugs either by contact or as a 'stomach poison'. The characteristic effects of metaldehyde poisoning were immobilization broken by outbursts of unco-ordinated muscular activity and sliming which usually resulted in severe water loss. 24 hr. after treatment with moderate doses slugs were still abnormal and rarely fed within 30 hr. of treatment. It was not possible to determine the M.L.D. with the methods used, but 0·06 mg. solid metaldehyde taken orally could be lethal to slugs of 400–800 mg. body weight. Lethal effects were produced by contact of 1 hr. with concentrations equivalent to 0·0063 mg./cm.^{2}. Toxicity increased with rise in temperature and recovery from moderate doses was dependent on slugs being in a saturated or almost saturated atmosphere. No obvious gut lesions were found in slugs which had been dosed with or had eaten metaldehyde. Its action was not by depolymerization in the gut or body cavity. In the light of laboratory and small scale field trials it is suggested that broadcasting and spraying are the best methods of applying the material.

Since the discovery of the slug-killing properties of metaldehyde some twenty years ago much attention has been given to its use on a field scale (Barnes & Weil, 1942; Thomas, 1948). In the absence of adequate information on its mode of entry and method of action it is not possible to say whether the most effective use of metaldehyde is at present being made. The present investigation was therefore undertaken to study in detail the uptake of the material, its physiological action and the effect of changes in temperature and humidity on its action.

Methods and materials

Both culture-reared and freshly captured wild specimens of *Agriolimax reticulatus* (Müller) were used. These did not differ in their reactions to metaldehyde and the bulk of the experiments were carried out on 'wild' slugs. Unless stated to the contrary, all slugs were starved in a saturated atmosphere for 24 hr. before being used in an experiment and in practically all experiments each slug was kept in isolation in a Petri dish lined with moist filter-paper. Weight records were kept during many experiments.

In some experiments, slugs were anaesthetized simply by placing them in narrow 100 ml. beakers containing about 1 ml. of water, into which a slow stream of carbon dioxide was passed. Slugs could withstand this treatment for at least 1 hr. and even after 5 hr. continuous anaesthetization many slugs recovered without showing any abnormal effects. Different batches of slugs varied in their ability to withstand the effects of carbon dioxide. Sliming occurred during anaesthetization, and this often resulted in a large weight loss (see Table 1).

TABLE 1. *Weight loss induced by carbon dioxide treatment* (15–18° C.)

Slug	Weight before CO_2 treatment (mg.)	Weight loss after 1 hr. CO_2 treatment (%)	Weight loss after 24 hr. recovery at 100 % R.H. (%)
1	835	26·6	13·4
2	933	27·1	24·8
3	717	23·1	17·7
4	795	25·8	24·8
5	703	20·3	1·4
6	585	15·7	3·4

Solutions of metaldehyde were prepared by mechanically stirring an excess of finely powdered metaldehyde with distilled water for 24 hr. and filtering. Analysis showed that the filtrate contained only metaldehyde with no free acetaldehyde, the solubility being 0·018 % at 0·5° C.; 0·020 % at 17° C.; 0·026 % at 30° C. Neutral or alkaline solutions were very stable, and even after 6 months did not contain detectable amounts of acetaldehyde. For use in field trials where mechanical stirring is impracticable a sufficiently concentrated solution can be made by stirring a water suspension at intervals and allowing to stand overnight. For small-scale use, a toxic solution can be prepared by hanging a muslin bag containing coarsely broken 'Meta' tablets in a watering can.

Whilst A.R. metaldehyde was used for practically all experiments some trials were made using the soil fuel 'Meta'. There were no obvious differences in the actions of these two materials.

MODE OF ENTRY OF METALDEHYDE

The literature (see Barnes & Weil, 1942; Thomas, 1948) suggests that metaldehyde acts as a contact poison. The experimental evidence supporting this conclusion is scanty, and much of it open to the criticism that adequate precautions were not taken to prevent treated slugs from eating traces of metaldehyde. Jary & Austin (1937) reported that sliming occurred when minute quantities of metaldehyde were placed on slugs and that five out of fourteen treated slugs were dead on the day following treatment. Thomas (1948) described experiments made to check the statement of Persing (1944) that metaldehyde had a contact action on the snail *Helix aspersa*. According to Thomas, metaldehyde placed on the bodies of healthy snails '...is merely sloughed off with the mucus as is any inert dry powder such as finely divided limestone'. He concluded, therefore, that metaldehyde had no contact action on snails. Similar experiments on slugs are not described but Thomas appears to assume that metaldehyde must be eaten to produce a lethal effect. He does state, however, that the irritant effect (sliming) might possibly be due to some contact action either by metaldehyde or dry bran on slugs partially poisoned by metaldehyde.

To elucidate the mode of entry of metaldehyde the following tests were made to determine its fumigant, contact and 'stomach' action on *Agriolimax reticulatus*.

(1) *Fumigant action*

Twenty slugs were confined over metaldehyde in a saturated atmosphere, the perforated floor of the testing chamber being 2 cm. above the layer of metaldehyde. Twenty control animals were exposed over calcium carbonate. Even after 3 days' exposure the slugs were not obviously affected by metaldehyde and readily fed when offered lettuce, indicating that metaldehyde has no important fumigant action.

(2) *Contact action of powdered metaldehyde*

Powdered metaldehyde was placed on the backs of slugs, and control animals were treated in a similar way either with calcium sulphate or carbonate. The slugs were kept in a saturated atmosphere under constant observation with every precaution to ensure that the material was not eaten. Irrespective of the site of treatment the metaldehyde-treated *A. reticulatus* showed the following reactions at 15–17° C. Some 15–100 min. after application locomotion ceased, tentacles were withdrawn and constrictions appeared spasmodically over the head and body. During the ensuing period of immobilization which might last several hours, occasional outbursts of locomotor activity would occur but they lacked co-ordination. When stimulated with forceps, treated slugs would attempt to move, but since movements were not co-ordinated the animals remained on the same spot. Sliming always occurred. In some, a thick chalky slime was produced, but in the majority the slime was thin and practically colourless. The slime had a wetting action on metaldehyde. Although the slugs were immobilized, sliming always continued until the metaldehyde was sloughed off. Removal of the metaldehyde rarely took less than 30 min. but never more than 4 hr. Twenty-four hours after treatment slugs were never normal and rarely fed within the succeeding 24 hr. In some cases the metaldehyde-treated slugs died as a result of the treatment.

Slugs treated with calcium sulphate and carbonate were quite normal 24 hr. after treatment and in many cases fragments of chalk still adhered to the epidermis. There was no noticeable effect on activity and no sustained sliming to remove the material.

Under field conditions the foot of the slug would be the most likely surface to come into contact with metaldehyde. It proved difficult to keep the substance in contact with the foot for periods greater than 5 min. but even with such short periods of contact the effects recorded above were noted.

Experiments were also made on slugs under carbon dioxide anaesthesia to ensure that metaldehyde was not eaten during the experimental period. At the end of the treatment any powder remaining on the slugs was scraped or washed off and the slugs left in individual Petri dishes to recover from the anaesthetic. All metaldehyde-treated slugs showed toxic symptoms and a varying number died. The results of a typical experiment are shown in Table 2.

TABLE 2. *Contact action of powdered metaldehyde on anaesthetized* Agriolimax reticulatus (15–17° C.)

Length of treatment (hr.)	Condition of slugs 24 hr. after treatment: Powdered metaldehyde			Powdered calcium carbonate		
	Normal	Moribund	Dead	Normal	Moribund	Dead
1	13	2	3	16	1	1
3	8	2	8	18	0	0

(3) *Contact action of metaldehyde solution*

Even though chemical handbooks state that metaldehyde is insoluble in water, it was noticed that water which had been in contact with metaldehyde was irritant to slugs. Slugs were painted with drops of saturated metaldehyde solution coloured with methylene blue. Thus the path of a solution applied to the epidermis could be traced, establishing with certainty whether or not the mouth region of the slug became contaminated with metaldehyde. Trials showed that, providing the slug was held vertical with its head uppermost, then the back and tail portions could be flooded with liquid without contaminating the anterior foot or mouth regions. Control slugs were treated with distilled water coloured with methylene blue.

One to eight minutes after dabbing with saturated metaldehyde solution slugs became immobilized and secreted thick white slime. Abnormal behaviour lasted for 10–24 hr. and many slugs were killed by the treatment.

The contact effect was studied quantitatively by using filter-papers (9 cm. diameter) placed in Petri dishes and flooded with 2 ml. of 0·02 % metaldehyde solution (0·0063 mg./cm.^{2}). Single slugs were placed in such Petri dishes and left in contact with the solution for varying periods of time. Some experiments were made using filter-papers impregnated with metaldehyde from chloroform solutions over the range 0·002–0·2 %. The chloroform papers were thoroughly air-dried and then flooded with 1 ml. water before use; papers thus impregnated gave essentially the same results as those treated with aqueous solutions. The contact effect was also demonstrated by placing individual slugs in small rectangular cells in a paraffin block into which known amounts of aqueous solution could be introduced.

Slugs placed so that only the foot was in contact with the impregnated filter-paper quickly showed signs of metaldehyde poisoning. The various symptoms observed when solid metaldehyde was used were recorded but their onset was more rapid and their intensity greater. Within 5 min. of being placed on the paper, tentacles were withdrawn and locomotion ceased. Thick chalky slime would always appear 25–60 min. after contact, whereas when solid metaldehyde was used this type of sliming did not always occur. Results obtained from typical experiments with 0·02 % aqueous solution and using anaesthetized and unanaesthetized slugs are shown in Table 3. Contact with 0·002 % for 3 hr. produced up to 10 % deaths. Two other effects, immobilization and inhibition of feeding, are also important factors in the value of metaldehyde for slug control. Exposures as brief as 5 min. were sufficient to produce immobilization which, depending on the temperature conditions, lasted for 10–24 hr. (see p. 401). After contact with 0·002 % solution for intervals of 15 min. to 3 hr. some 50 % were able to feed within 24 hr. of treatment. Using 0·02 % marked differences in feeding ability were noted, depending on the length of treatment. Neglecting those slugs killed by the treatment, 50 % were able to feed within 2 days after 15 min. treatment and within 3 days after 1 and 3 hr. contact.

TABLE 3. *Contact action of metaldehyde solution on* Agriolimax reticulatus

Length of treatment (hr.)	Metaldehyde solution			Controls (distilled water)		
	Normal	Moribund	Dead	Normal	Moribund	Dead
	(*a*) Anaesthetized slugs (16–19° C.)					
1	6	3	3	12	0	0
3	4	3	11	13	2	3
5	0	3	18	10	3	8
	(*b*) Unanaesthetized slugs (18–22° C.)					
1	10	0	2	12	0	0
3	1	0	11	12	0	0

TABLE 4. *Weight losses (mg.) induced by contact with metaldehyde solution*

Length of treatment (hr.)	Metaldehyde solution		Controls (distilled water)	
	After treatment	After 24 hr.	After treatment	After 24 hr.
1	$-21·99 \pm 3·52$	$-24·29 \pm 6·77$	$-1·98 \pm 4·24$	$-4·66 \pm 3·77$
3	$-26·93 \pm 5·24$	$-32·6 \pm 6·68$	$+8·3 \pm 6·6$	$+6·75 \pm 4·41$

After exposure to filter-paper impregnanted with 0·02 % metaldehyde solution, slugs were placed in Petri dishes containing moist filter-papers.

Even though slugs were maintained at 100 % R.H. during and after contact treatment, weight losses of 25–35 % were recorded, chiefly water loss (see Table 4). Water loss via sliming and water uptake could occur simultaneously: for example, slugs dehydrated for 5 hr. (weight loss 25–50 %) would slime copiously on metaldehyde-treated filter-papers, but after 1 hr. contact they usually showed weight increases of up to 10 %. Controls similarly dehydrated showed gains of 25–50 % in 1 hr. when placed on filter-papers moistened with distilled water.

These experiments fully support the observations of Jary & Austin (1937). Metaldehyde can exert a contact effect as a solid or in solution, and if contact is sufficiently prolonged its action may be lethal.

(4) *Metaldehyde as an internal poison*

(*a*) *Metaldehyde solution*

Metaldehyde solutions were injected into the crop via the mouth using an 'Agla' micro-injection syringe fitted with a glass capillary tube shaped to pass through the buccal mass and down the slender oesophagus. The delivery end of the tube was bulb-shaped to prevent laceration of the tissues and the escape of liquids from crop to mouth during the course of injection. To ensure that slugs in which regurgitation occurred were not included in the assessment of results, solutions were coloured with methylene blue.

The amount of solution which could be passed into the crop without regurgitation was limited to 0·1–0·2 ml. for *A. reticulatus* weighing 300–800 mg. In only a few cases, out of many trials, was 0·2 ml. injected without some regurgitation occurring.

Quantities as small as 0·01 ml. (≡0·002 mg.) induced symptoms of metaldehyde poisoning, and these were very marked with the maximum amount (0·1 ml.≡0·02 mg.). The various effects described for the contact experiments were observed in injected slugs but they were slower to appear and, apart from copious white sliming, were never so intense. At 20° C., using the maximum dose (0·1 ml.) 28 % (approx.), mortality was recorded within 3 days of injection (Table 6). Injected slugs did not feed in the 36 hr. period following injection.

(*b*) *Metaldehyde powder*

Methods. Micro-injection guns were used to force known amounts of dry materials such as powdered metaldehyde into the buccal cavity and crop of slugs. These were constructed either from hypodermic needles with the ends cut off or from fine-bore stainless steel tubing. The guns had tight-fitting plungers made from pivot steel and were loaded by pressing the delivery end into a small heap of finely powdered test material, the plunger being sufficiently withdrawn to allow the substance to be packed into the shaft. After this preliminary loading the shaft was pressed until the loading mark was just visible above the tube. When a high degree of accuracy was necessary this operation was carried out under a binocular-dissecting microscope. This movement, if the loading had been effective, resulted in a small cylinder of test material protruding from the delivery end. With a steady pressure on the plunger, the delivery end was again pressed into a small heap of test substance, ensuring that the end of the tube was uniformly packed. Surplus material was carefully wiped off. Each gun was calibrated by filling the instrument and then weighing the amount ejected. In the guns of very fine bore (0·18 mm.) graduations were not necessary for it was only possible, using the procedure described above, to pack a small length of the column with powder.

The accuracy of the method was low. Whilst different guns, when carefully loaded, were capable of ejecting the following amounts of metaldehyde: 0·32 ± 0·1, 0·24 ± 0·1 and 0·06 ± 0·04 mg., it was not possible to make any allowance for errors introduced in the course of injecting metaldehyde into test animals. Particles adhered to the guns to a varying extent after withdrawal and using very small amounts (< 0·1 mg.) it was never possible to determine whether all or part of the injected material had been regurgitated.

In order to obtain concentrations of metaldehyde below the content of the smallest gun used (0·06 mg.) the substance was diluted with either glucose or calcium sulphate or carbonate. Comparative trials failed to show any specific effect of the diluent on the activity of the metaldehyde.

Both anaesthetized and non-anaesthetized slugs were used in the experiments. In most experiments slugs were dissected to determine whether the metaldehyde had remained in the animal and whether any injuries had been caused by the injection. The death-rate from the injection procedure was negligible.

Results. As might be expected, slugs reacted more slowly to the presence of solid metaldehyde than to dissolved metaldehyde. Results of different experiments carried out under standard conditions varied over a wide range, and it was evident that the experimental technique was too crude and the reactions of the animals too variable to permit an accurate assessment of the median lethal dose. In Table 5 percentages are given based on a number of different experiments. In view of the many sources of error, known and unknown, it is clear that the figures represent no more than the trends shown with different dosage rates. Death from metaldehyde poisoning was long drawn out. As Table 5 shows, even at high dosage rates deaths were still occurring 3 days after treatment and the greater part of the material could be recovered from the gut after death. In a few cases metaldehyde was actually defaecated.

TABLE 5. *Lethal action of powdered metaldehyde injected into the crop of* Agriolimax reticulatus

Amount injected (mg.)	No. of slugs	Percentage kill Days after injection 1	2	3
0·003	30	0	0	0
0·01	40	5	10	15
0·03	40	22	30	35
0·06	80	30	56	66
0·22	30	63	87	—

No deaths were recorded in the controls which were injected with calcium sulphate. All experiments were carried out at 20° C.

From these investigations on the mode of entry of metaldehyde it is clear that the material can exert its effects both by contact and as an internal poison.

Mode of action of metaldehyde

(1) *Injection of solutions into the haemocoel*

Since slugs reacted to internal doses less rapidly than to external treatment, it would seem that the material was not rapidly transported from the gut. The effect of injecting metaldehyde solution directly into the haemocoel was therefore studied.

Methods. An 'Agla' syringe fitted with an ordinary fine injection needle was used. In preliminary trials to test the influence of site of injection on sensitivity to metaldehyde, batches of slugs were injected either on the dorsal, lateral or ventral surfaces at one of the following positions: anterior to the mantle; posterior to the mantle; tail region. The nine injection sites were compared and the effects produced were found to be similar. In the detailed investigations therefore, injections were made in the middle region of the foot. Solutions were coloured with methylene blue, and even unanaesthetized slugs could be injected with amounts up to 0·15 ml. with little loss of fluid. In all experiments equal numbers of control slugs were injected with water coloured with methylene blue.

Results. Injection of 0·1 ml. metaldehyde directly into the haemocoel produced an immediate reaction. Usually before the whole amount had been injected the slug was completely immobilized and thick white slime was copiously produced. Even amounts as small as 0·01–0·02 ml. (0·002–0·004 mg.) produced this immediate reaction. From Table 6 it is evident that the lethal effect was subject to greater variation than that shown in oral injections and contact treatment. On the whole, slugs recovered more rapidly from haemocoel injections than from contact treatment or crop injections.

Table 6. *Comparison of the lethal action of oral injection, haemocoel injection and contact treatment* (20° C.)

Oral injection, 0·1 ml.	Haemocoel injection, 0·1 ml.	Contact with 0·1 ml. for 3 hr.
8·75 ± 1·7	6·75 ± 3·13	10·37 ± 1·77

These means refer to the deaths recorded per twenty-five slugs 3 days after treatment. They are based on nine experiments in each of which twenty-five slugs were treated in each group. Contact treatment was carried out in paraffin-wax cells (see p. 395). The maximum death-rate in controls treated with water was three per twenty-five slugs.

Control slugs injected with equivalent amounts of water were not immobilized by the treatment and showed normal activity and feeding immediately after injection. Some white slime was usually produced at the time of injection, but the animals in spite of the shock-effect of the treatment always showed a gain in weight, whereas those given metaldehyde showed a marked weight loss (Table 7).

Table 7. *Weight changes* (mg.) *produced by injections into the haemocoel*

Metaldehyde solution (100 mg.)		Controls (distilled water 100 mg.)	
1 hr. after treatment	24 hr. after treatment	1 hr. after treatment	24 hr. after treatment
−66 ± 31·4	−78 ± 29·0	± 83·5 ± 34·7	+ 58·3 ± 31·4

(2) *The action of acetaldehyde and paraldehyde*

The effects of acetaldehyde, paraldehyde and metaldehyde were compared with the aim of elucidating the mode of action of metaldehyde.

Contact action was tested by the normal filter-paper technique. At both 15 and 20° C. slugs were quite normal even after 3 hr. contact with 2·0 % solutions of either acetaldehyde or paraldehyde, whereas 0·02 % metaldehyde produced the toxic effects already described. Further, the two former solutions did not produce toxic symptoms when injected orally or directly into the haemocoel. Whilst some immobilization was shown, slugs recovered sufficiently to move about and eat within 24 hr. of treatment.

These observations show that the toxic effects of metaldehyde are not due to the formation of acetaldehyde and are not equivalent to the action of paraldehyde. The fact that acetaldehyde is without toxic action even at concentrations 100 times greater than that of the usual metaldehyde solution would suggest that any depolymerization occurring in the gut or blood of slugs would result in a lessening of the toxic action of the material.

(3) *Histological effects of metaldehyde*

Thomas (1948) states that the gut wall becomes transparent as a result of metaldehyde poisoning, and when this condition is reached the slug will eventually die. To determine the extent of this change slugs killed by metaldehyde and an equal number poisoned by carbon dioxide were dissected. These observations showed no transparency in the metaldehyde-treated slugs which was not of normal post-mortem origin. Transparency results from a sloughing off of the thin mucous membrane of the crop and this occurred whatever the cause of death, for it was noted both in culture slugs and in field slugs which were found dead. Further, metaldehyde does not accelerate the removal of the mucous membrane. Crops excised from healthy slugs were ligatured at both ends after having small amounts of metaldehyde pushed into them and kept in *Helix* Ringer (Pantin, 1946) along with similarly prepared controls containing equivalent amounts of calcium carbonate or calcium sulphate. Under such conditions as far as macroscopic inspection showed, the membranes remained healthy up to 24 hr.

(4) *Effect of temperature and humidity*

Slugs are without a waterproofing layer, and in an unsaturated atmosphere lose water passively to the environment (Howes & Wells, 1934). Death from desiccation can take place rapidly; for instance at 70 % R.H. (15° C.) slugs will die from desiccation in 7–17 hr. It is obvious, therefore, that if slugs suffer from metaldehyde poisoning and are immobilized, their loss of water due to sliming coupled with exposure to low humidities will produce death. This was verified in the course of the investigations. It was also shown that metaldehyde-treated slugs exposed to saturated atmospheres were not able to regain their water content at the same rate as untreated slugs.

High temperature enhances the toxicity of metaldehyde (see Table 8). Detailed studies on 'contact'-treated slugs showed that temperature influenced both uptake and toxicity. Thus, slugs placed in contact with metaldehyde at 15° C. for 3 hr., and then kept at 20° C. for 21 hr. showed a lower death-rate than slugs kept at 20° C. throughout the experiment or kept at 20° C. for treatment followed by 21 hr. at 15° C. This temperature effect is certainly of practical importance, and it helps to explain one of the findings of Thomas (1948) who concluded on the basis of field trials that wet warm nights followed by dry warm days gave the highest catches and highest mortalities. It is now clear that warmth whilst influencing the activity of slugs also increases the toxic action of metaldehyde.

TABLE 8. *Effect of temperature on the toxic action of metaldehyde*

Quantity of metaldehyde (ml.)	Exposure (hr.)	No. of slugs used at each temperature	Deaths 24 hr. after treatment 15° C.	20° C.
0·1	1	25	1	6
0·1	3	30	0	11
0·2	1	35	1	7
0·2	3	70	7	36

FIELD TRIALS WITH METALDEHYDE SOLUTION

To assess the toxicity of metaldehyde solutions to slugs under field conditions the following experiments were carried out.

(1) *Field exposure of laboratory-treated slugs*

Slugs were placed in contact with metaldehyde solution using paraffin block cavities just large enough to contain single slugs and up to 0·2 ml. solution. Slugs were left in contact with the solution for 5 min., 15 min., or 3 hr., then removed and the surplus liquid absorbed by filter-paper. Treated slugs were then placed in the garden on bare rough soil under a coarse mesh wire-netting cage to exclude birds. Control slugs were treated with water and also placed out of doors under wire-netting cages. Field exposure began in the late afternoon (16 hr., G.M.T. approx.) and counts were made the following morning to determine the number killed and the number which had been able to seek shelter.

It is evident from Table 9 that even 5 min. contact with the solution was sufficient to produce a degree of immobilization lasting 10–24 hr. under field conditions. Furthermore, given warm, dry conditions a high mortality was recorded with such a treatment.

(2) *Container experiments*

In these experiments galvanized iron containers 60 cm. long and 26 cm. diameter with bottoms and tight-fitting lids of perforated tin were filled with soil to within 10–15 cm. of the brim and sunk in the ground so that the outside and inside soil levels were approximately the same. The soil surface within the container was slightly compacted and made relatively smooth.

Metaldehyde solution (0·02 %) was applied to the soil surface within the containers to give the following amounts in mg./m.² of metaldehyde: 75, 226, 376, 488 (equivalent to 20, 60, 100 and 130 ml. of solution per container). Controls were similarly sprayed with 20 ml. water. (In laboratory experiments with impregnated filter-papers toxic effects were obtained with 2 ml. per filter-paper which is equivalent to 63 mg./m.².)

TABLE 9. *Effect of field conditions on laboratory-treated slugs*

Date, 1951	Period of contact and temperature	No. on soil after 24 hr.		No. killed		Weather
		Treated	Controls	Treated	Controls	
12 March	3 hr. (20° C.)	10	2	0	0	Snow
20 March	3 hr. (20° C.)	9	9	2	0	Heavy frost
5 April	3 hr. (20° C.)	9	10	9	2	Windy; very dry
6 April	3 hr. (20° C.)	9	0	9	0	Dry
10 April	15 min. (15° C.)	9	0	0	0	Frost
12 April	15 min. (15° C.)	10	1	0	1	Windy; dry
26 July	15 min. (18° C.)	10	2	9	1	Warm; showery
26 July	15 min. (18° C.)	8	0	8	0	Warm; showery
9 April	5 min. (15° C.)	6	0	6	0	Warm; dry
10 April	5 min. (15° C.)	9	0	0	0	Frost
12 April	5 min. (15° C.)	10	1	10	1	Wind; dry
26 July	5 min. (18° C.)	5	–	5	–	Warm; showery
26 July	5 min. (18° C.)	10	–	8	–	Warm; showery

In each experiment ten treated and ten control slugs were placed under field conditions. Columns 3 and 4 show the number of slugs found on the soil surface with little or no shelter. In the case of metaldehyde-treated slugs 80 % were discovered within a radius of 25 cm. of the site of deposition, whereas many control slugs had travelled over 1 m.

The soil in the containers was sprayed with the appropriate solution at approx. noon (G.M.T.), then 2½–3 hr. later, ten *A. reticulatus* together with unsprayed lettuce were placed in the container. The condition of the slugs was recorded at approximately 24 hr. intervals over a period of 3–5 days.

Results. The total deaths recorded in typical experiments, together with temperature and humidity data, are shown in Fig. 1. Under warm dry conditions mortality was 100 % at all concentrations, although the control slugs laid eggs and fed quite normally under the same physical conditions. Cool and wet weather at the beginning of an experiment decreased total mortality (Expts. 3 and 5), but even under such conditions 100 % mortality still occurred in the cylinders sprayed with 488 mg./m.².

Observations made on slugs at various times of the day confirmed the known effects of humidity and temperature on metaldehyde-treated slugs. On warm days many slugs which appeared normal or only slightly abnormal in the morning would be moribund or dead in the afternoon. On the other hand, slugs which appeared to be moribund in the afternoon would recover if overnight conditions were cool and wet. Feeding is greatly affected by metaldehyde treatment. Although some feeding was recorded at all except the highest concentrations it was never so extensive as that shown by the controls.

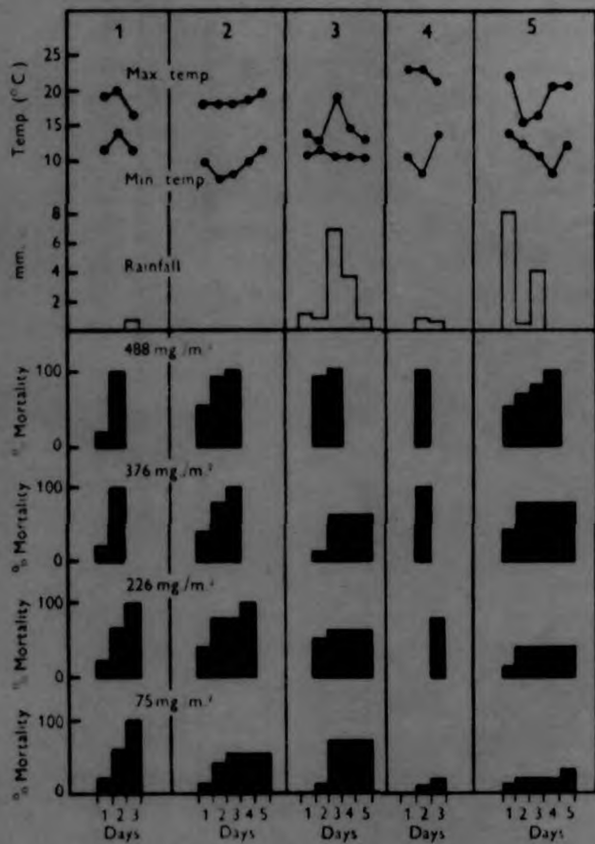

Fig. 1. Histograms of five experiments to show the lethal effect of different amounts of metaldehyde solution under field conditions. The amount of metaldehyde solution is expressed as milligrams of metaldehyde per square metre.

Even though conditions within the tins were not equivalent to normal field conditions the experiments demonstrated that metaldehyde solutions were toxic when applied to soil.

(3) *Experiments using large slug-proof enclosures*

To simulate natural conditions as far as possible, and yet be able to make counts on known samples of slugs, a slug-proof enclosure, 100 cm. long × 90 cm. deep was made out of phosphor-bronze gauze (1 mm. mesh). At the corners, uprights of 2 cm. diameter conduit piping were firmly wired to the outside of the gauze. Around the upper edge an iron frame 0·3 cm. thick × 2·5 cm. deep was soldered to the outside. The lid of phosphor-bronze, with its edges also strengthened by an iron frame, fitted over the box, and to ensure a 'slug-proof' condition the inner edge of the lid was lined with strip rubber of the 'draught-excluder' type. This bottomless box was sunk into the ground to a depth of 45 cm., thus leaving an extensive air space above soil level.

Three types of experiment were made, using saturated metaldehyde solution in all at the rate of 500 mg./m.^{2} (2½ l.) and an equivalent amount of water for the controls. After each experiment the contaminated soil was removed to a depth of 20 cm. and replaced with fresh soil.

Series I. The soil surface was sprayed approx. at noon (G.M.T.). Three to four hours later, four white tiles (15 × 15 cm.) to provide cover, fifty *A. reticulatus* and a few unsprayed lettuce leaves were placed on the soil. These experiments were essentially of the same type as those described as 'container experiments'.

Series II. Slugs were placed in the pen along with tiles and lettuce at 11 hr. (G.M.T.) and allowed to seek shelter. When the contents of the pen were sprayed 3–4 hr. later, no slugs were visible.

Series III. In these experiments the pen was not sprayed, but lettuce was soaked in the solution and then placed in an otherwise metaldehyde-free pen in which fifty slugs had already been placed and taken shelter. The treated lettuce was removed after 24 hr. and replaced by fresh (unsprayed) lettuce.

TABLE 10. *Effect of metaldehyde solution under field conditions*

No. of exp.	Duration (days)	Max. temp. (range °C.)	Rainfall (mm.)	Occurrence of feeding	Slugs found dead (%)
		Series I. Slugs placed on sprayed soil			
1	4	12–15	10·3	None	68
2	2	22–24	0	None	96
3	4	15–23	12·5	None	96
		Series II. Slugs under cover at time of spraying			
1	5	13–21	10·4	Moderate	28
2	4	17–23	0·7	Slight	92
3	3	15–24	1·1	Slight	96
		Series III. Only food material sprayed			
1	3	12–21	2·8	Moderate	36
2	4	15–18	4·5	Moderate	10
3	5	11–20	1·4	Moderate	0

Fifty slugs were used in each experiment. Extensive feeding occurred in all control batches and no deaths were recorded.

From Table 10 it is clear that metaldehyde solution can exert a lethal effect under field conditions, the best results being achieved where the material was applied generally to the surfaces likely to be traversed by slugs. In Series III, where slugs were exposed to sprayed food material for 1 day, the lethal effect was small in spite of the fact that the treated lettuce was eaten extensively. The daily counts did show, however, that a majority of slugs remained immobilized on the soil surface for some period during the first 2 days. Given dry warm conditions the death-rate would no doubt have been greater.

In general, these experiments emphasize the value of the contact action of metaldehyde, at the same time indicating its non-persistent nature and its dependence on suitable weather conditions.

DISCUSSION

This investigation proves that metaldehyde can exert a toxic action on *A. reticulatus* either by contact or as a 'stomach' poison; the toxic effects appearing more rapidly in contact treatment. Metaldehyde stimulates water loss via mucus secretion, produces immobilization (the 'anaesthetic effect' of Thomas, 1948) and inhibits feeding. With moderate doses complete recovery may occur providing the slugs are kept in a saturated atmosphere. The recovery rate is greatest at low temperatures. Death from metaldehyde poisoning is not due simply to desiccation, for it can occur even when slugs are kept at 100 % R.H. and when the treatment has induced only a moderate water loss.

The data so far available suggest that metaldehyde is a nerve poison, but how it produces its various effects is not known. Its toxic action is clearly not dependent on depolymerization prior to absorption at the site of action.

Now that two modes of entry are known to occur it should be possible to place the field use of the material on a more rational basis. To make the fullest use of the contact effect spraying or broadcasting would appear to be the simplest method of application.

A saturated solution can bring about the death of slugs under field conditions and it can inhibit feeding. Obviously it is not persistent and would need frequent applications to ensure a high degree of control. Greater concentrations of the material could be obtained by applying it as a suspension. In horticulture it might be applied when non-edible plants were being watered and it should be of value as a preventive spray applied to hedgerow bottoms, in protecting seed-beds and plants cultivated for decoration. At present, in view of the known toxic effects of metaldehyde on man (Lewis, Madel & Drury, 1939) it would not be advisable, without detailed investigation, to use the solution on a large scale on edible crops, although it is unlikely because of its non-persistent nature, that toxic doses would remain on sprayed plants.

At present, solid metaldehyde is usually used in bait form, the bait being spaced about the area in small heaps or as 'biscuits'. According to Barnes & Weil (1942) the efficiency of baiting is dependent upon the presence of a suitable attractant such as bran. Thomas (1948) has shown that his biscuit form has the added advantages that it does not break up very readily in wet weather and that it is more resistant to attack by moulds. While there is much to be said for attracting slugs to the material when it is used in the form of discrete heaps, it should be possible, relying on chance contact action, to dispense with an attractant when broadcasting metaldehyde. Thomas (1948) clearly showed his 'broken-biscuit' preparation when broadcast to be more effective than the usual bran-metaldehyde mixture. Now that the value of the contact effect has been established, trials should be carried out to determine whether bran in the 'broken-biscuit' preparation can be replaced by a 'non-food' carrier without impairing the efficacy of the material.

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