Zeitschrift: Acta Tropica
Herausgeber: Schweizerisches Tropeninstitut (Basel)
Band: 36 (1979)
Heft: 4

Artikel: Immunization against "Nippostrongylus brasiliensis" in the rat : a study on the use of antigen extracted from adult parasites and the parameters which influence the level of protection

Autor: Murray, M. / Robinson, P.B. / Grierson, C.

DOI: https://doi.org/10.5169/seals-312534

Acta Tropica *36*, 297–322 (1979)

Department of Veterinary Pathology, Glasgow University Veterinary School,
Bearsden Road, Bearsden, Glasgow, Great Britain

Immunization against *Nippostrongylus brasiliensis* in the rat

A study on the use of antigen extracted from adult parasites and the parameters which influence the level of protection

M. Murray, P. B. Robinson, C. Grierson, R. A. Crawford

Summary

It was found that protective immunity in excess of 90% reduction in worm burden could be stimulated against *Nippostrongylus brasiliensis* in rats by using an extract of adult *Nippostrongylus* worms. The level of protection achieved was influenced by several factors. Thus, the use of *Bordetella pertussis* as adjuvant significantly increased the level of protection which, in addition, was shown to be influenced by the amount of worm antigen used. Furthermore, antigen administered in multiple doses was more effective than a single inoculum and, when using such a regime, the interval between doses was also found to be critical. The route of antigen administration was important and, while protection was achieved by subcutaneous and oral administration, the intraperitoneal route was the most effective. Using the optimal immunization regime of 3 doses of 5 mg worm protein and 4×10^{10} *B. pertussis* organisms, as adjuvant, levels of protective immunity in excess of 90% reduction in worm burden were shown to exist for at least 60 days after the last dose. It was found that adult worm extracts did not stimulate any obvious immunity against larval forms of *N. brasiliensis.*

Key words: nematode; *Nippostrongylus brasiliensis;* adult worm extracts; immunization; protection; worm burden; egg output; mast cells; reaginic antibodies; *Bordetella pertussis;* adjuvant; dose of antigen; number of doses and interval between; route of administration; memory.

Introduction

Despite the availability of effective drugs and of other control measures, helminth disease remains one of the major health problems of man and his

Correspondence: Dr. Max Murray, International Laboratory for Research on Animal Diseases, P.O. Box 30709, Nairobi, Kenya

domestic animals. So far, only in the domestic animals are effective vaccines commercially available. These include vaccines against *Dictyocaulus viviparus* in cattle (Jarrett et al., 1960a) and *Dictyocaulus filaria* in sheep (Jovanović et al., 1965). Such vaccines employ as immunogen larvae attenuated by X-irradiation. A similar approach has been adopted with several other economically and socially important diseases. In some cases the results have been highly successful such as with *Ancylostoma caninum* in dogs (Miller, 1965) and with *Syngamus trachea* in chickens (Varga, 1968) while in other instances the level of protection obtained was promising but now awaits further development (reviewed by Urquhart et al., 1962).

The other approach to the development of helminth vaccines has been the use of killed worm antigens; these include worm homogenates, worm extracts and metabolic products. So far the results with non-living material have usually been considered equivocal and disappointing (Ogilvie and Jones, 1973), although there are a number of studies demonstrating significant levels of protection against nematodes, cestodes and trematodes (see discussion).

Recent advances in immunology have indicated that the host's immune response can be modulated to achieve a desired response and many of the variables involved in producing selective immunologic effects have been delineated. At the same time, there has been increasing understanding of the immunologic effector mechanisms operative in the helminth infections. Thus, there is a case for reconsidering the production of further helminth vaccines.

In the present study, using the model system of *Nippostrongylus brasiliensis* in the rat, ways of manipulating the host's protective response to killed adult worm antigen were examined with a view to achieving optimal protection. It was found that high levels of protection can be obtained using non-living parasitic material and that several factors can influence the outcome. These factors include the use of adjuvant, the dose of antigen, the number of doses given and the interval between them, and the route of administration.

Materials and methods

In nippostrongylosis, following systemic migration of infective larvae from a subcutaneous inoculation site, adult worms become established in the small intestine 5 days later. Following a stable phase, the parasites are expelled exponentially after day 10; this is preceded by a drop in worm egg output. The slope of the line showing the kinetics of worm expulsion is taken as a measure of the immune status of the host (Jarrett et al., 1968). Associated with worm expulsion there is an exponential increase in the number of intestinal mast cells and reaginic antibody levels in the serum become elevated (Miller and Jarrett, 1971; Murray, 1972). Thus, the parameters employed in the present study to judge the protective response to various vaccination regimes were worm burden, worm egg output, intestinal mast cell numbers and serum reaginic antibody response. Protection achieved was expressed as a percentage of the reduction in geometric mean worm number in the treated groups in comparison with the challenge controls.

Adult female hooded Lister rats aged 8 to 10 weeks and weighing approximately 150 g were used in all experiments. The parasite culture was prepared after the modified method of Bakarat (1951) adapted by Jennings et al. (1963). The technique of worm recovery from the small intestine

was described by Mulligan et al. (1965). Total worm counts were carried out in all cases in order to eliminate the sampling error caused by worm clumping. Faecal egg counts were done after the method of Gordon and Whitlock (1939).

Small intestinal tissues collected for mast cell quantitation were fixed and stained as described by Miller and Jarrett (1971). Intestinal mast cells were quantified on a villus-crypt (VC) unit basis in groups of 5 to 10 rats after the method of Miller and Jarrett (1971).

Serum from each group of rats was pooled and titrated for reaginic antibody activity by the passive cutaneous anaphylaxis test (PCA) performed in parasite-free rats. PCA was carried out by intradermal injection of doubling serial serum dilutions (0.1 ml), each dilution being duplicated in separate test animals. Seventy-two hours later, the rats were injected intravenously with 0.5 ml of *N. brasiliensis* antigen (containing 1 mg worm protein) in 0.5 ml of 1% Evans Blue. The rats were sacrificed 30 min later. The reagin titre was recorded as the reciprocal of the greatest dilution which gave skin reaction sizes of greater than 5 mm.

Adult worm antigen extract for use in vaccination studies and reaginic antibody estimations was prepared as follows. Rats were inoculated subcutaneously with 3000 to 5000 third stage *N. brasiliensis* larvae and were sacrificed 7 days later. The adult worms were harvested as described above and then washed repeatedly in phosphate buffered saline. The worms were then homogenised in an icebath using a Silverson Emulsifier (Silverson Machines Ltd.). The resultant homogenate was spun at 1700 *g* in a refrigerated centrifuge for 30 min to remove the larger worm fragments and eggs and then at 100,000 *g* for 50 min. The protein content of the resultant supernatant was estimated by the Lowry technique (Lowry et al., 1951) and then aliquots were stored at –20° C. Throughout these procedures, particular attention was paid to maintaining worm homogenates in the cold.

The *Bordetella pertussis* (Wellcome Research Laboratories) used as adjuvant was a killed bacterial suspension containing 4×10^{10} organisms/ml. The standard dose employed in these studies was 4×10^{10} organisms given intraperitoneally.

All experiments used groups of 10 to 20 rats. The worm antigen and the adjuvant were administered intraperitoneally by separate inoculation but at the same time. Immunized rats were challenged subcutaneously with 3000 third stage *N. brasiliensis* larvae, unless otherwise stated, and were sacrificed 10 days later, just prior to the onset of worm expulsion in susceptible challenge control rats (Murray et al., 1971). Rats subjected to reinfection were inoculated with 3000 *N. brasiliensis* larvae at the start of the experiment and challenged with 3000 larvae at the same time as the vaccinated groups.

Prior to analysis, logarithmic transformation (to base 10) of worm burden and mast cell data was carried out. This transformation linearises the relationship between worm count or mast cell numbers and time where an exponential situation exists, as it does with *N. brasiliensis* (Jarrett et al. 1968; Miller and Jarrett, 1971), and normalises the data for statistical analysis. The studentised range test (Miller, 1966) was used to identify different groups. Values of $P<0.05$ were considered significant. All results in the text concerning worm counts and mast cell numbers are expressed as geometric means (GM) and standard error of the $\log_{10}$ values. In the tables, the results were given as geometric means and the pooled standard error of the $\log_{10}$ values, SE ($\log_{10}$).

Results

Several preliminary experiments established that significant levels of protection could be achieved against *N. brasiliensis* in the rat using whole adult worm extract, e.g., one group of 12 rats, which received 2 inoculations of 5 mg worm protein intraperitoneally at a 30 day interval and challenged 10 days later with 3000 *N. brasiliensis* larvae, was found to harbour 475 ± 0.15 worms 10 days later as compared with 968 ± 0.03 worms in the challenge controls, a significant 50% reduction in worm burden.

Table 1. Effect of the adjuvant *Bordetella pertussis* on worm burden, intestinal mast cells and reaginic antibody levels in rats immunized against *Nippostrongylus brasiliensis*

	Group				
	1	2	3	4	5
No. of rats	20	20	20	20	20
Preparation	Antigen/*B. pertussis*	Antigen	*B. pertussis*	Reinfection	Challenge controls
Vaccine regime					
dose in mg worm protein	5	5	–	–	–
no. of doses	3	3	3	–	–
dose interval in days	7	7	7	–	–
days to challenge	10	10	10	24	–
Worm burden, GM ± pooled SE ($\log_{10}$)	19 ± 0.17^{b}	243 ± 0.17^{c}	1157 ± 0.17^{d}	4 ± 0.17^{a}	1161 ± 0.17^{d}
% protection	98	79	0	99	–
Mast cells/VC, GM ± pooled SE($\log_{10}$)					
before*	11 ± 0.02^{b}	9 ± 0.02^{a}	9 ± 0.02^{c}	35 ± 0.02^{c}	9 ± 0.02^{a}
after	6 ± 0.13^{b}	5 ± 0.13^{b}	1 ± 0.13^{a}	70 ± 0.13^{c}	1 ± 0.13^{a}
Reaginic antibody titre	1/1024	1/16	0	1/1024	0

Different subscripts indicate different groups by the studentised range test at a 5% significance level.
* 5 rats were sacrificed from each group prior to challenge.

The following series of experiments examined several parameters which might affect levels of protection. These parameters included the influence of adjuvant, the importance of dose of antigen, comparison of the effect of single or multiple doses, the effect of the interval between doses, and the importance of the route of administration of antigen. In addition, the site of action of adult worm antigen was considered as was the duration of immunity.

Influence of adjuvant

B. pertussis was chosen as adjuvant because of its established ability to potentiate sensitivity to mast cell-mediated anaphylaxis (Mota, 1958), a response possibly important in immunity to *N. brasiliensis* (reviewed by Murray, 1972).

It was found that the simultaneous administration of *B. pertussis* with whole adult worm extracts significantly increased the level of protection obtained. Table 1 shows the results of a typical experiment and the experimental procedure. With worm antigen alone, the average level of protection was 79%. When *B. pertussis* was also administered the level of protection rose to 98%, a significant increase. This was almost of the same order found in rats immunized with live parasites (99%). *B. pertussis* alone had no protective effect. The results were reflected by higher levels of intestinal mast cells and reaginic antibodies and also by a quicker reduction in worm egg output in the protected groups (Table 2).

In a similar experiment using smaller amounts of worm protein, 2 mg per dose, comparable although slightly reduced levels of protection were obtained. The number of worms recovered from antigen/*B. pertussis* immunized rats was 113 ± 0.23, the antigen alone group contained 800 ± 0.4 worms, while the challenge controls harboured 1327 ± 0.03 worms. Thus, the level of protection rose significantly from 40% to 91%, simply by the additional use of the adjuvant *B. pertussis.* As in the previous experiment, these results were reflected by a quicker reduction in worm egg output and a significant increase in intestinal mast cells and serum reaginic antibody response in the protected groups.

Table 2. Effect of the adjuvant *Bordetella pertussis* on worm egg output/g faeces in rats immunized against *Nippostrongylus brasiliensis*

Group	Preparation	Days after challenge		
		8	9	10
1	Antigen/*B. pertussis*	24,900	1,500	0
2	Antigen	36,200	5,900	2,400
3	*B. pertussis*	38,100	30,000	17,100
4	Reinfection	600	150	0
5	Challenge controls	34,000	25,000	19,200

Table 3. Effect of antigen dose on worm burden, intestinal mast cells and reaginic antibody levels in rats immunized against *Nippostrongylus brasiliensis*

	Group			
	1	2	3	4
No. of rats	12	12	12	12
Preparation	Antigen/*B. pertussis*	Antigen/*B. pertussis*	Antigen/*B. pertussis*	Challenge control
Vaccine regime:				
dose in mg worm protein	1	10	30	–
no. of doses	1	1	1	–
days to challenge	10	10	10	–
Worm burden, GM ± pooled SE(log_{10})	740 ± 0.11^{b}	630 ± 0.11^{b}	77 ± 0.11^{a}	991 ± 0.11^{b}
% protection	25	36	92	–
Mast cells/VC, GM ± pooled SE(log_{10})	2.2 ± 0.16^{a}	6.5 ± 0.16^{b}	11.2 ± 0.16^{b}	1.0 ± 0.16^{a}
Reaginic antibody titre	1/512	1/1024	1/1024	1/16

Different subscripts indicate different groups by the studentised range test at a 5% level.

Effect of antigen dose

The result of the above 2 experiments suggested that the dose of antigen administered might have influenced the level of protection achieved. In order to evaluate the importance of dose in relation to protection, three groups of rats were immunized with three different amounts of worm antigen. The results are shown in Table 3. It was found that there was a significant correlation between the dose of antigen used and the degree of the protection obtained. The average protection achieved by 1 mg, 10 mg and 30 mg worm protein was 25%, 36% and 92%, respectively, as judged by reduction in worm burden. As before, this was reflected by an increase in intestinal mast cells and by reaginic antibody titres. The worm egg output was markedly reduced in the most effectively protected group.

Single or multiple immunizing doses

In order to evaluate the potential influence of single or multiple doses on protection, 3 groups of rats were given a total of 15 mg worm protein on one, two or three separate occasions. Ten days after the last inoculum they were challenged with 2000 *N. brasiliensis* larvae (Table 4).

Significantly higher levels of protection (99%) were achieved when a triple dose was given at weekly intervals than when only one dose was administered (93%). When 2 doses were given at a 30 day interval significant protection was obtained but it was lower (71%) than with the other regimes. These results were again reflected by a more rapid drop in worm egg output and a significant increase in intestinal mast cells and reaginic antibody titres in protected rats.

Influence of the interval between immunizing doses

A possible explanation for the lower level of protection obtained in the previous experiment, when two doses of worm antigen were given at a 30 day interval, was that the interval between doses is critical and that 30 days was too long to obtain suitable priming and a good secondary response in this particular system. Thus, an experiment was carried out with 2 groups of 12 rats; one group received 2 doses of 7.5 mg worm protein at a 7 day interval while the other group was given the same amount at a 30 day interval. The adjuvant *B. pertussis* was used with each dose. The rats were challenged 10 days later with 3000 *N. brasiliensis* larvae. When sacrificed 10 days later the level of protection produced in the rats receiving the immunizing doses at a 7 day interval was 89% (worm burden = 116 ± 0.18), as judged by the percentage reduction in worms. This was significantly higher than in the group of rats which were immunized at a 30 day interval; the level of protection in this group was 61% (worm burden = 429 ± 0.14), confirming that the time interval between immunizing doses is a critical consideration in vaccine protocols. The number of worms recovered from the challenged controls was 1110 ± 0.03.

Table 4. Effect of multiple or single doses of worm antigen on worm burden, intestinal mast cells and reaginic antibody levels in rats immunized against *Nippostrongylus brasiliensis*

	Group			
	1	2	3	4
No. of rats	10	10	10	10
Preparation	Antigen/*B. pertussis*	Antigen/*B. pertussis*	Antigen/*B. pertussis*	Challenge controls
Vaccine regime:				
dose in mg worm protein	5	15	7.5	–
no. of doses	3	1	2	–
dose interval in days	7	–	30	–
total dose in mg worm protein	15	15	15	–
days to challenge	10	10	10	–
Worm burden, GM ± pooled SE($\log_{10}$)	3 ± 0.18^{a}	37 ± 0.18^{b}	163 ± 0.18^{c}	568 ± 0.18^{d}
% protection	99	93	71	–
Mast cells/VC, GM ± pooled SE($\log_{10}$)	40 ± 0.1^{c}	12 ± 0.1^{b}	11 ± 0.1^{b}	4 ± 0.1^{a}
Reaginic antibody titre	1/1024	1/512	1/256	1/4

Different subscripts indicate different groups by the studentised range test at a 5% significance level.

Table 5. Effect of route of administration on worm burden, intestinal mast cells and reaginic antibody levels in rats immunized against *Nippostrongylus brasiliensis*

	Group			
	1	2	3	4
No. of rats	10	10	10	10
Preparation	Antigen/*B. pertussis*	Antigen/*B. pertussis*	Antigen/*B. pertussis*	Challenge control
Vaccine regime				
route of administration of antigen	Intraperitoneal	Subcutaneous	Oral	–
dose in mg worm protein	10	10	10	–
No. of doses	2	2	2	–
dose interval in days	10	10	10	–
days to challenge	10	10	10	–
Worm burden, GM ± pooled SE($\log_{10}$)	41 ± 0.1^{a}	229 ± 0.1^{b}	661 ± 0.1^{c}	1026 ± 0.1^{c}
% protection	96	77	35	–
Mast cells/VC, GM ± pooled SE($\log_{10}$)	16.3 ± 0.11^{b}	14.5 ± 0.11^{b}	2.3 ± 0.11^{a}	1.9 ± 0.11^{a}
Reaginic antibody titre	1/1024	1/512	1/128	0

Different subscripts indicate different groups by the studentised range test at a 5% significance level

Table 6. Effect of time to challenge on worm burden, intestinal mast cells and reaginic antibody levels in rats immunized against *Nippostrongylus brasiliensis*

	Group			
	1	2	3	4
No. of rats	12	12	12	12
Preparation	Antigen/*B. pertussis*	Antigen/*B. pertussis*	Antigen/*B. pertussis*	Challenge control
Vaccine regime				
dose in mg worm protein	5	5	5	–
no. of doses	3	3	3	–
dose interval in days	7	7	7	–
days to challenge	60	30	10	–
Worm burden, GM ± pooled SE(log_{10})	15 ± 0.29^{a}	9 ± 0.29^{a}	28 ± 0.29^{a}	1127 ± 0.29^{b}
% protection	98	99	97	–
Mast cells/VC, GM ± pooled SE(log_{10})	3 ± 0.12^{b}	7 ± 0.12^{c}	14 ± 0.12^{c}	1 ± 0.12^{a}
Reaginic antibody titre	1/2048	1/4096	1/4096	0

Different subscripts indicate different groups by the studentised range test at a 5% significance level.

Importance of route administration

In the present series of experiments, it was shown that the protective effect of antigen prepared from adult worms appears to be effective only when the parasites have matured to the adult stage and are in the small intestine (see later). Thus, it was decided to compare the efficacy of the local or oral route of administration with parenteral ones. It was found that the oral administration of antigen produced only low levels of protection (35%) and was much less effective than the parenteral routes, where the subcutaneous route (77%) was found to be inferior to the intraperitoneal one (96%) (Table 5).

As with other experiments, reaginic antibody titres and intestinal mast cell numbers were increased and correlated with the level of protection achieved.

Duration of immunity achieved using killed adult worm antigen

In order to examine the duration of immunological memory induced using killed worm antigen, three groups of rats were immunized using the vaccine procedure found to be optimal in the present study, namely, 3 doses of 5 mg worm protein inoculated intraperitoneally at intervals of 7 days. 4×10^{10} organisms of *B. pertussis* were given intraperitoneally with each dose. One group of rats was challenged 10 days, one at 30 days and another at 60 days after the last inoculation. It was found that high levels of immunity were maintained for at least 60 days (Table 6). Significantly increased levels of intestinal mast cells and elevated reaginic antibody titres corresponded with the protective responses achieved.

Site of action of killed adult worm vaccine

There was some evidence in the previous experiments, as judged by worm egg output, that following immunization and challenge adult worms became established in the small intestine of immunized rats. To examine this possibility and to define at what stage of the parasite life cycle this particular vaccine was operative, an experiment was carried out in which immunized rats were sacrificed on day 6 as well as day 10 after challenge. The results are shown in Table 7. On day 6 there was no difference in the number of parasites established in the small intestine of the vaccinated animals as compared with the challenge controls. By day 10, however, there was a highly significant reduction of over 90% in the vaccinated groups. This result indicated that the killed adult worm vaccine was effective only against the adult parasites and apparently showed no cross reactivity against migrating larval forms. In the protected rats, there was a corresponding increase in the number of intestinal mast cells and in the serum reaginic antibody levels.

The result obtained from the group of rats immunized with only one dose of antigen, while showing no significant difference from the group which received 3 doses, once again gave some indication that dose was an important factor in induction of protective immunity.

Table 7. Site of action of adult worm antigen vaccine

	Group		
	1	2	3
No. of rats	20	20	20
Preparation	Antigen/*B. pertussis*	Antigen/*B. pertussis*	Challenge control
Vaccine regime:			
dose in mg worm protein	5	5	–
no. of doses	3	1	–
dose interval in days	7	–	–
days to challenge	10	10	–
Worm burden, GM ± pooled SE(log_{10}):			
day 6	1150 ± 0.03^{a}	1303 ± 0.03^{a}	1151 ± 0.03^{a}
day 10	29 ± 0.18^{a}	68 ± 0.18^{a}	1143 ± 0.18^{b}
% protection	97	94	–
Mast cells/VC, GM ± pooled SE(log_{10})			
day 6	4 ± 0.13^{b}	3 ± 0.13^{b}	1 ± 0.13^{a}
day 10	8 ± 0.1^{c}	3 ± 0.1^{b}	1 ± 0.1^{a}
Reaginic antibody titre			
day 6	1/1024	1/256	0
day 10	1/4096	1/1024	0

Different subscripts indicate different groups by the studentised range test at a 5% significance level.

Discussion

The results of the present study have shown that significant levels of protection can be obtained in rats against the nematode *N. brasiliensis* using a killed adult worm antigen extract. This confirmed the findings of several other groups of workers (Chandler, 1932; 1936; Watt, 1943; Thorson, 1951; 1953; Denham, 1968; 1969a; Poulain et al., 1976) apart from Ogilvie (1967) who failed to produce any resistance using an adult worm extract of *N. brasiliensis.* One possible explanation for this discrepancy was that the dose of antigen used for immunization in Ogilvie's (1967) experiments was too low.

There are numerous studies with several other nematode parasites where the use of killed parasite antigen or their metabolic products for immunization resulted in significant levels of protection. These include: *Trichinella spiralis* (McCoy, 1935; Campbell, 1955; Chute, 1956; Chipman, 1957; Ewert and Olson, 1960; 1961; Denham, 1967; Despommier and Muller, 1969; Larsh et al., 1970; Vernes, 1976; Despommier et al., 1977), *D. viviparus* (Jarrett et al., 1960b; Wade et al., 1961; Wade et al., 1962; Silverman et al., 1962; Robinson, 1967), *Trichostrongylus colubriformis* (Silverman et al., 1962; Connan, 1965; Denham 1969b; Rothwell and Love, 1974; Rothwell, 1978), *Haemonchus contortus* (Ozerol and Silverman, 1970; Silverman and Paterson, 1960; Scott et al., 1971), *Oesophagostomum radiatum* (Keith and Bremner, 1973), *Ostertagia circumcincta* (Rose 1976; 1978), *A. caninum* (Thorson, 1956), *Nematospiroides dubius* (Van Zandt, 1962; Cypess, 1970), *Trichuris muris* (Wakelin and Selby, 1973; Jenkins, 1976; Jenkins and Wakelin, 1977), *Ascaris suum* (Fallis, 1948; Lejkina, 1953; Soulsby, 1957; 1963; Rhodes et al., 1965; Crandall and Arean, 1965; Guerrero and Silverman, 1969; 1971; Bindseil, 1969; Stromberg and Soulsby, 1977), *Ascaridia* species (Rebrassier and McCrory, 1931; Eisenbrant and Aekert, 1940, both quoted by Ershov, 1959), *Strongyloides papillosus* (Silverman et al., 1962), *Strongyloides ratti* (Sheldon, 1973) and *Litomosoides carinii* (MacDonald and Scott, 1953). These results were obtained in a wide range of laboratory and domestic animal hosts including cattle, sheep, pigs, dogs, mice, rats, rabbits, guinea pigs and chickens.

Significant levels of protection have also been achieved with several cestode parasites using killed worm antigen or their metabolic products in both definitive and in intermediate hosts. Sheep have been immunized against *Cysticercus tenuicollis* (Gemmell, 1969), *C. ovis* (Gemmell, 1969; Rickard and Bell, 1971; Rickard et al., 1976; Rickard et al., 1977) and *Moniezia expansa* (Seddon, 1930; Puklov and Velitchkin, 1936, quoted by Ershov, 1959), while cattle have been successfully protected against *C. bovis* (Gallie and Sewell, 1976; Rickard and Adolph 1976; Rickard et al., 1977). Furthermore, significant levels of protection have been achieved in rats against *C. fasciolaris* (Miller, 1930; 1931a; 1931b; 1932; Campbell, 1936; Kwa and Liew, 1977) and in rabbits against *C. pisiformis* (Miller and Kerr, 1932; Kerr, 1935; Heath, 1976). Turner et al.

Table 8. Studies in which non-living material has been successfully used for immunization

Species	Parasite	Antigen preparation	Adjuvants	% protection	Authors
Guinea pig	*T. colubriformis*	Soluble extract or metabolic products* of fourth stage larvae	Freund's complete**	>90	Rothwell and Love (1974)
Guinea pig	*T. colubriformis*	Soluble extract of fourth stage larvae	Aluminium hydroxide	>90	Rothwell (1978)
Guinea pig	*D. viviparus*	Lyophilized third stage, fourth stage larvae and their metabolic products	Aluminium hydroxide	>90	Silverman et al. (1962)
Guinea pig	*A. suum*	Killed third stage larvae and their metabolic products	Freund's complete	>90	Soulsby (1963)
Mouse	*T. spiralis*	Extract of oesophageal gland of the parasite	Freund's complete	>90	Despommier and Muller (1969)
Mouse/ Mini pig	*T. spiralis*	Metabolic products of muscle larvae	Freund's complete** *Corynebacterium parvum***	>90	Vernes (1976)
Mouse	*T. muris*	Extract of adult worms	Freund's incomplete	>90	Wakelin and Selby (1973)
Mouse	*T. muris*	Extract of adult worms Metabolic products of adult worms	Freund's incomplete Freund's incomplete	>90 >90	Jenkins and Wakelin (1977)
Rabbit	*S. papillosus*	Lyophilized third stage, fourth stage larvae and their metabolic products	Aluminium hydroxide	>90	Silverman et al. (1962)
Rat	*N. brasiliensis*	Metabolic products of adult parasites	*B. pertussis*	>90	Denham (1969a)
Rat	*S. ratti*	Heat killed larvae	None	>90	Sheldon (1937)
Sheep	*C. ovis*	Metabolic products of activated embryos	Freund's complete	100	Rickard and Bell (1971)
Sheep	*C. ovis*	Metabolic products of *Taenia ovis* larvae	Freund's incomplete	>90 100	Rickard et al. (1976) Rickard et al. (1977)
Sheep	*C. tenuicollis*	Formalized or frozen activated embryos	None	>90	Gemmell (1969)
Sheep	*M. expansa*	Ground up proglottids	None	100***	Seddon (1930)
Bovine	*C. bovis*	Metabolic products of *Taenia saginata* larvae	Freund's incomplete	>90 to 100	Rickard & Adolph (1976) Rickard et al. (1977)
Bovine	*C. bovis*	Proglottid homogenate of *Taenia saginata*	Freund's complete	100	Gallie & Sewell (1976)
Rat	*C. fasciolaris*	Somatic antigen of strobilocerci. Metabolic product of strobilocerci Purified somatic antigen of strobilocerci (MW = 140,000 daltons)	Freund's complete Freund's complete Freund's complete	>90 >90 100	Kwa and Liew (1977)
Rabbit	*C. pisiformis*	Killed larvae with metabolic products	None	>90	Heath (1976)
Mouse	*H. nana*	Adult worm homogenate	Aluminium hydroxide	>90	Coleman et al. (1968)

* Metabolic products are antigens obtained from in vitro cultures of live parasites.

** Adjuvant used with no obvious effect.

*** Only one animal studied.

(1932, 1936) were able to produce high levels of protection in dogs against *Ecchinococcus granulosus.* Using an adult worm preparation, both Larsh (1944) and Coleman et al. (1968) were able to produce significant levels of protection in mice to *Hymenolepis nana,* while Kowalski and Thorson (1972) stimulated protection in mice against *Mesocestoides corti* using metabolic products and a soluble somatic antigen.

Attempts to induce resistance to trematodes by artificial immunization with killed worm antigen have met with very limited success and have often given conflicting results. Adult worm antigen or metabolic products of *Schistosoma japonicum* produced a limited reduction in worms in rabbits (Kawamura, 1929), dogs (Kawamura, 1929; Ozawa, 1930) and in mice (Lin et al., 1954; Sadun and Lin, 1959; Sadun, 1963), whereas, in a study involving 2 monkeys Vogel and Minning (1953) failed to stimulate any protective immunity. With *S. mansoni* limited success has been reported in mice and rats using adult worm preparations (Watts, 1949; Sadun, 1963; Sadun and Bruce, 1964), soluble cercarial immunogen (Phillips et al., 1978) or metabolic products of cercariae and adults (Kagan, 1958; Levine and Kagan, 1960; Murrell and Clay, 1972). Several other groups have failed completely (Thompson, 1954; Ritchie et al., 1962) or obtained inconsistent results (Sher et al., 1974; Murrell et al., 1975).

Published results with other trematodes using killed worm antigen are few and probably reflect the limited success obtained. Attempts to produce resistance to infection with *Fasciola hepatica* using non-living whole fluke preparations or their extracts have given equivocal results. Some workers have reported measurable acquired resistance in rabbits (Kerr and Petkovich, 1935; Shibanai et al., 1956), in mice (Lang, 1976; Lang and Hall, 1977) and in sheep (Ershov, 1959), as judged by reduction in the number of adult worms recovered. Others have failed to substantiate these results (Hughes, 1962). In other studies, some evidence of immunity was obtained in rabbits as judged by reduction in worm size and fecundity but not worm numbers (Urquhart et al., 1954; Healy, 1955; Ross, 1967). Our own preliminary observations in rats have shown that partial but significant levels of protection can be achieved against *F. hepatica* providing large amounts of adult fluke protein and an adjuvant are used.

In the above studies, a wide range of parasite preparations were used to induce protective immunity. These included parasite antigens prepared and inactivated using a variety of methods, including physical and chemical procedures, as well as a range of worm extracts. In addition, there are several reports in which larval or adult worm metabolic products, prepared in vitro, were shown to have protective qualities, in some cases of a very high nature. Furthermore, it was found that at least some of the antigens concerned with protective immunity were likely to have originated from ducted glands in the parasite and were possibly enzymes. Thus, extracts from the anterior or stichosomal region of several nematodes including *A. caninum* (Thorson, 1956), *T. spiralis* (Despommier and Muller, 1969), *O. radiatum* (Keith and Bremmer, 1973) and *T. muris*

(Wakelin and Selby, 1972; Jenkins and Wakelin, 1977) have been shown to stimulate significant levels of protection. The speculation that these protective factors are secretory and might represent enzymes has been supported by the findings of Rhodes et al. (1965) and Edwards and Gutteridge (1968) who were able to stimulate protection using malic dehydrogenase extracted from *A. suum* and *N. brasiliensis* respectively. In a more recent study, however, Rothwell and Merritt (1975) found that the capacity of various extracts of *T. colubriformis* to stimulate protective immunity was not related to their acetylcholinesterase content and that a highly purified fraction of acetylcholinesterase was not effective.

In the majority of studies on immunization with non-living worm material it should be emphasized that the levels of protection achieved, although significant, were in most cases not as high as those obtained with attenuated parasites (Urquhart et al., 1962). However, there are reports in which very high levels of protection have been achieved showing that killed antigen, at least from some parasites, is highly immunogenic and has potential application (Table 8). It is worth noting in these studies that in 13 cases metabolic products were employed in the vaccine, in 16 adjuvant was effectively used, while the dose of antigen was carefully titrated in at least 5 studies.

In the present studies, it was found that several factors influenced protection and if properly manipulated the level of protection achieved by killed adult worm antigen extract was consistently increased to levels of more than 90%. These factors included the use of adjuvant, the quantity of worm protein given, the number of doses employed and the interval between them, and the route of administration of the antigen.

In designing a vaccine regime, the choice of adjuvant is likely to be important and should be based on an understanding of the host's effector mechanisms in dealing with the parasite and also its site of action. *In nippostrongylosis*, for example, there is evidence that worm expulsion is associated with a worm allergen – mast cell – reaginic antibody interaction at the gut level (Barth et al., 1966; Murray, 1972). It has been found in the intestinal mucosa of the rat infected with *N. brasiliensis* that mast cell discharge with the release of vasoactive compounds is associated with the opening up of intercellular pathways between endothelial cells and between epithelial cells, thereby creating enhanced mucosal permeability to macromolecules (Murray et al., 1971). In the intestinal mucosa of the rat most of the IgE is associated with mast cells and not plasma cells (Mayrhofer et al., 1976). Thus, it is possible to envisage a highly specific role for IgE and mast cells at mucous surfaces, namely, that of facilitating translocation of protective antibody or other effector substances across the epithelial sheet of the mucous membrane. This hypothesis has been supported by findings of Steinberg et al. (1975) who showed that IgE facilitated protective antibody release across the vascular barrier and termed it the "gateway" antibody. Thus, because of its well established ability to potentiate reaginic antibody reactions

(Mota, 1958), *B. pertussis* was selected as the adjuvant for the present investigation. As a result of its use with killed adult worm extract in this study, it was possible to increase protection to levels consistently in excess of 90%.

In previous studies on immunization against helminth infection using non-living parasite material, adjuvants have occasionally been used sometimes with significant effect. Denham (1967), studying *T. spiralis* in the mouse, found that both Freund's complete adjuvant and *B. pertussis* increased protection levels, although *B. pertussis* was superior. Denham (1968, 1969a) went on to show in a preliminary report the effectiveness of *B. pertussis* as an adjuvant in vaccination against *N. brasiliensis* in rats. The use of aluminium hydroxide enhanced protection levels achieved in guinea pigs against *D. viviparus* and in rats against *S. papillosus* (Silverman et al., 1962). Aluminium hydroxide was also effective when used in a vaccine against *T. colubriformis* in guinea pigs (Rothwell, 1978), whereas Freund's complete and incomplete adjuvant had little effect (Rothwell and Love, 1974) indicating that the choice of the correct adjuvant is critical. On the other hand, Wakelin and Selby (1973) found that the use of Freund's incomplete or complete adjuvant significantly increased protection to *T. muris* in mice.

It should also be emphasised that not only is the choice of adjuvant critical but so too is the dose of adjuvant, its route of administration and its time of administration in relation to antigen and dose of antigen; all of these factors are important in deciding which effector arm of the immune response is stimulated (Leskowitz and Waksman, 1960; Dresser and Philips, 1973; WHO, 1976). The number of adjuvants available for use in potential helminth vaccines is limited and it is generally agreed that more should be developed (WHO, 1976). Helminths themselves are able to induce a wide range of responses in the host's immune system, e.g., the nematode *N. brasiliensis* has been shown to potentiate a specific immunoglobulin class response to an heterologous protein antigen (Orr and Blair, 1969). Extending this, Jarrett (1972) used a *N. brasiliensis* infection superimposed on a *F. hepatica* infection in the rat to potentiate the reaginic antibody response to *F. hepatica.* Thus, parasites or their extracts might offer a rich source of potential compounds which could be used as adjuvants.

Another factor shown in the present study to have a critical influence on protection was the dose of antigen employed; there was a direct correlation between the dose of antigen and the level of protection achieved. This finding was in agreement with the results of several other groups including Turner et al. (1936) with *E. granulosus* in the dog, Silverman et al. (1962) with *D. viviparus* in the guinea pig. Despommier et al. (1977) with *T. spiralis* in mice, Poulain et al. (1976) with *N. brasiliensis* in rats, Rothwell and Love (1974) and Rothwell (1978) with *T. colubriformis* in guinea pigs, Lang and Hall (1977) with *F. hepatica* in mice and Kwa and Liew (1977) with *T. taeniaeformis* in rats.

Under most circumstances, it is usually necessary to give 2 or more spaced antigenic stimuli to achieve a good immune response. Furthermore, it has been

found that a suitable time interval between antigenic stimuli and adequate secondary antigen doses is important in induction of an high secondary response (Nakashima et al., 1974). Thus, in the present study on helminth protective immunity it was shown that 2 or more vaccine doses gave significantly better results than one. The time interval between the doses was also confirmed to be critical in that the level of protection achieved when the vaccine was given at monthly intervals was significantly less than when given at weekly intervals. Similarly, Silverman et al. (1962), studying vaccination against *D. viviparus* in guinea pigs, found that the interval between vaccine doses was important and in their studies established that 21 days was the optimal period.

In developing a vaccine strategy, it is essential to consider the site inhabited by the parasite in order that the immune response can be maximised at that particular location. Several factors are known to influence the site at which the immune response is operative; these include route of administration, dose of antigen and whether the antigen is live or dead (Spencer et al., 1974; Bienenstock, 1975; Frederick and Bohl, 1976). In the present study, the level of protection was found to be influenced by the route of immunization. The intraperitoneal route gave the best results and was superior to the subcutaneous and the oral route which was poorest. Vernes (1976), studying vaccination against *T. spiralis* in mice and minipigs using metabolic antigens from muscle larvae, confirmed that the route of vaccination was important but that the oral route gave superior results to the subcutaneous route. On the other hand, Rothwell (1978) found the oral route for administration of vaccine to be inferior to subcutaneous, intradermal, intraperitoneal and intraduodenal routes. The level of protection obtained in the present experiment using the oral route was disappointing when one considers that adult *Nippostrongylus* parasites inhabit the small intestine and that the antigen used was apparently only effective against adult parasites. The results probably reflect degradation of worm protein by the gastrointestinal tract and possibly the potential difficulty in establishing good immunological memory at local mucous surfaces (Murray, 1973; Waldmann and Ganguly, 1975). To overcome this problem it might be necessary to administer antigen repeatedly at the local level in order to reach and maintain satisfactory levels of immunity. Alternatively, it is known that the administration of large amounts of antigen parenterally will stimulate both systemic and local responses (Spencer et al., 1974; Bienenstock, 1975) and it would appear that this was what was achieved by the use of the intraperitoneal route in the present study.

It is usually considered that one of the potential disadvantages of the use of a killed antigen, is a rapid waning of immunity. However, in the present study, it was found that the use of a triple dose of worm antigen with adjuvant given intraperitoneally stimulated high levels of immunity demonstrable for at least 2 months after the last vaccine inoculation. Despommier and Wostmann (1968) were able to demonstrate persistence of protective immunity in mice by in-

traperitoneal implantation of diffusion chambers containing *T. spiralis* larvae; strong immunity still existed 6 months after removal of the chambers. In one of the first demonstrations of artificially-stimulated protective immunity, Miller (1932) found that good protective immunity lasted in the rat for as long as 167 days after the last immunizing dose with a dried powdered adult worm preparation of *T. taeniaeformis*, while, using culture antigen of *T. ovis* larvae in Freund's incomplete adjuvant to vaccinate sheep, Rickard et al. (1977) showed that high levels of protective immunity lasted for at least one year after vaccination.

The use of antigen prepared from adult *Nippostrongylus* worms produced no apparent cross reactivity to the larval challenge in that in immunized rats the expected adult population became established in the small intestine, as judged by the challenge controls. Only then did the immunological effector mechanisms potentiated by vaccination become operative. It is significant to observe on the basis of this finding that the adjuvant *B. pertussis* had helped to potentiate effector mechanisms operative at the level of the mucous surface. Thus, the site of action of protective effector mechanisms induced by this immunization regime is distinct from that which exists in rats subjected to a reinfection regime where it has been shown that increased resistance is due, at least in part, to the fact that a significant proportion of the challenge infection is killed as larvae in the lungs (Jarrett et al., 1968).

While in certain cases considerable success has attended the use of irradiated parasitic vaccines, there are a large number of helminth infections in which the use of irradiated parasites has produced significant but not commercially exploitable levels of protective immunity (Urquhart et al., 1962). It is possible that, if the parameters highlighted in this paper as being important in protective immunity were considered, this situation might be improved.

The potential advantages and disadvantages involved in the use of a dead or living attenuated vaccine are well recognized. Dead vaccines are likely to have a good shelf life and less likely to produce any pathological side effects, both disadvantages of attenuated vaccines. On the other hand, attenuated vaccines are likely to stimulate stronger and longer lasting immunity. Perhaps the use of dead or living immunogens should not be considered mutually exclusive and their possible use in combination be examined, e.g., a priming inoculation of killed antigen followed by a booster with attenuated antigen might stimulate a strong and long lasting immunity with reduced danger of pathological side effects.

In conclusion, in planning the strategy of any vaccination regime, a basic understanding is required of the host's immune effector mechanisms, as is an appreciation of the logistics and parameters of the immunological engineering programme which might be required. These parameters should include, the nature of the antigen (live or dead), dose of antigen, number of doses and interval between doses of antigen, and the use and choice of adjuvants. The fact that protection, sometimes of a high order, can be achieved using non-living parasit-

ic material should encourage research into the isolation and characterization of helminth protective antigens, the nature of which remains largely unknown at present. It would appear from the evidence gleaned from the literature and described in the present study that metabolic products obtained from in vitro parasite cultures might be a rewarding starting point. The presentation to the host of purified protective antigens rather than the plethora of antigens usually given in most killed antigen preparations, is likely to produce a much more effective protective response.

Acknowledgments. We would like to thank Miss Rosemary Brown for her technical assistance and the Wellcome Trust for financial support.

1 Bakarat M. R.: A new procedure for the cultivation of the nematode parasites. J. Egypt. med. Ass. *34*, 323–326 (1954).
2 Barth Ellen E. E., Jarrett W. F. H., Urquhart G. M.: Studies on the mechanism of the self-cure reaction in rats infected with *Nippostongylus brasiliensis*. Immunology *10*, 459–464 (1966).
3 Bienenstock J.: The local immune response. Amer. J. vet. Res. *36*, 488–491 (1975).
4 Bindseil E.: Immunity to *Ascaris suum*. I. Immunity induced in mice by mean of material from adult worms. Acta path. microbiol. scand. *77*, 218–222 (1969).
5 Campbell C. H.: The antigenic role of the excretions and secretions of *Trichinella spiralis* in the production of immunity in mice. J. Parasit. *41*, 483–491 (1955).
6 Campbell D. H.: Active immunization of albino rats with protein fractions from *Taenia taeniaeformis* and its larval form *Cysticercus fasciolaris*. Amer. J. Hyg. *23*, 104–113 (1936).
7 Chandler A. C.: Experiments on resistance of rats to superinfection with the nematode *Nippostrongylus muris*. Amer. J. Hyg. *16*, 750–782 (1932).
8 Chandler A. C.: Studies on the nature of immunity to intestinal helminths. IV. The interrelations between parenteral and intestinal immunity in rats infected with *Nippostrongylus*. Amer. J. Hyg. *24*, 129–144 (1936).
9 Chipman P. B.: The antigenic role of the excretions and secretions of adult *Trichinella spiralis* in the production of immunity in mice. J. Parasit. *43*, 593–598 (1957).
10 Chute R. M.: The dual antibody response to experimental trichinosis. Proc. Helminth Soc. Wash. *23*, 49–58 (1956).
11 Coleman R. M., Corty Janice, Graziadei W. D.: Immunogenicity and phylogenetic relationship of tapeworm antigens produced by *Hymenolepis nana* and *Hymenolepis diminuta*. Immunology *15*, 297–304 (1968).
12 Connan R.: Immunity in the guinea-pig to *Trichostrongylus colubriformis* – a study of the antigen associated with immunity. Parasitology *55*, 10 (1965).
13 Crandall Catherine A., Arean V. M.: The protective effect of viable and non viable *Ascaris suum* larvae and egg preparations in mice. Amer. J. trop. Med. Hyg. *14*, 765–769 (1965).
14 Cypess R.: Artificial production of acquired immunity in mice by footpad infections of a crude larval extract of *Nematospiroides dubius*. J. Parasit. *56*, 320 (1970).
15 Denham D. A.: Applications of the in vitro culture of nematodes especially *Trichinella spiralis*. In: Problems of in vitro culture (ed. by Angela E. R. Taylor), p. 49–50. Blackwell Scientific Publications, Oxford/Edinburgh 1967.
16 Denham D. A.: *Bordetella pertussis* vaccine as an adjuvant for helminth antigens. J. Parasit. *54*, 68 (1968).
17 Denham D. A.: Secretion of metabolic antigen by *Nippostrongylus brasiliensis* in vitro. J. Parasit. *55*, 676–677 (1969a).
18 Denham D. A.: The immunity of lambs against *Trichostrongylus colubriformis*. J. comp. Path. *79*, 1–6 (1969b).

19 Despommier D. D., Wostmann B. S.: Diffusion chambers for inducing immunity to *Trichinella spiralis* in mice. Exp. Parasit. *23*, 228–233 (1968).
20 Despommier D. D., Muller M.: Particle-associated, functional antigens of *Trichinella spiralis* larvae and immunity in mice. Wiadomosci Parazytologiczne. Proc. 2nd int. Conf. on Trichinellosis, Warsaw. *15*, 612 (1969).
21 Despommier D. D., Campbell W. C., Blair L. S.: The in vivo and in vitro analysis of immunity to *Trichinella spiralis* in mice and rats. Parasitology *74*, 109–119 (1977).
22 Dresser D. W., Phillips J. M.: The cellular targets for the action of adjuvants: T-adjuvants and B-adjuvants. In: Immunopotentiation. Ciba Foundation Symposium 18 (ed. by J. Knight and G. E. H. Wolstenholme), p. 3–28. Elsevier, Amsterdam 1973.
23 Edwards A. J., Gutteridge W. E.: Presence, properties and partial purification of malate dehydrogenases in *Nippostrongylus brasiliensis.* Parasitology *59*, 21P–23P (1969).
24 Ershov V. S.: The problem of immunization of domestic animals to Helminthoses. Proc. 16th intern. vet. Congr., Madrid, p. 279–289 (1959).
25 Ewert A., Olson L. J.: Immunological tolerance studies with mice and *Trichinella.* J. Parasit. *46*, 849–854 (1960).
26 Ewert A., Olson L. J.: The use of a mouse oral LD50 to evaluate the immunogenicity of *Trichinella* metabolic antigens. Tex. Rep. Biol. Med. *19*, 580–584 (1961).
27 Fallis M. A.: *Ascaris lumbricoides* infection in guinea pigs with special reference to eosinophilia and resistance. Canad. J. Res. *D26*, 307–327 (1948).
28 Frederick G. T., Bohl E. H.: Local and systemic cell-mediated immunity against transmissible gastroenteritis, an intestinal viral infection of swine. J. Immunol. *116*, 1000–1004 (1976).
29 Gallie G. J., Sewell M. M. H.: Experimental immunization of six months old calves against infection with the cysticercus stage of *Taenia saginata.* Trop. anim. Hlth Product. *8*, 233–242 (1976).
30 Gemmell M. A.: Immunological responses of the mammalian host against tapeworm infection. X. Immunization of sheep against *Taenia hydatigena* and *T. ovis* with chemically or physically-treated embryos. Exp. Parasit. *26*, 58–66 (1969).
31 Gordon H. McL., Whitlock H. V.: A new technique for counting nematode eggs in sheep faeces. J. Council sci. indust. Res. Australia *12*, 50–52 (1939).
32 Guerrero J., Silvermann P. H.: *Ascaris suum:* immune reactions in mice. I. Larval metabolic and somatic antigens. Exp. Parasit. *26*, 272–281 (1969).
33 Guerrero J., Silverman P. H.: *Ascaris suum:* immune reactions in mice. II. Metabolic and somatic antigens from in vitro cultured larvae. Exp. Parasit. *29*, 110–115 (1971).
34 Healy G. R.: Studies on immunity to *Fasciola hepatica* in rabbits. J. Parasit. *41*, 25 (1955).
35 Heath D. D.: Resistance to *Taenia pisiformis* larvae in rabbits. Immunization against infection using non-living antigens from in vitro culture. Int. J. Parasit. *16*, 19–24 (1976).
36 Hughes D. L.: Observations on the immunology of *Fasciola hepatica* infections in mice and rabbits. Parasitology *52*, 4 (1962).
37 Jarrett Ellen E. E., Jarrett W. F. H., Urquhart G. M.: Quantitative studies on the kinetics of establishment and expulsion of intestinal nematode populations in susceptible and immune hosts. *Nippostrongylus brasiliensis* in the rat. Parasitology *59*, 625–640 (1968).
38 Jarrett Ellen E. E.: Potentiation of reaginic (IgE) antibody to ovalbumin in the rat following sequential trematode and nematode infections. Immunology *22*, 1099–1101 (1972).
39 Jarrett W. F. H., Jennings F. W., McIntyre W. I. M., Mulligan W., Urquhart G. M.: Immunological studies on *Dictyocaulus viviparus* infection. Immunity produced by the administration of irradiated larvae. Immunology *3*, 145–151 (1960a).
40 Jarrett W. F. H., Jennings F. W., McIntyre W. I. M., Mulligan W., Urquhart G. M.: Immunological studies on *Dictyocaulus viviparus* infection. Active immunization with whole worm vaccine. Immunology *3*, 135–144 (1960b).
41 Jennings F. W., Mulligan W., Urquhart G. M.: Variables in x-ray "inactivations" of *Nippostrongylus brasiliensis* larvae. Exp. Parasit. *13*, 367–373 (1963).

42 Jovanović M., Sokolić A., Movsesijan M., Cuperlović K.: Immunization of sheep with irradiated larvae of *Dictyocaulus filaria.* Brit. vet. J. *121*, 119–131 (1965).
43 Kagan I. G.: Contributions to the immunology and serology of schistosomiasis. The Rice Inst. Pamphlet *45*, 151–183 (1958).
44 Kawamura R.: The recent researches on *Schistosomiasis japonica* in Japan. Jap. med. Wld. *9*, 165–170 (1929).
45 Keith R. K., Bremner K. C.: Immunization of calves against the nodular worm, *Oesophogostomum radiatum.* Res. vet. Sci. *15*, 123–124 (1973).
46 Kerr K. B.: Immunity against a cestode parasite *Cysticercus pisiformis.* Amer. J. Hyg. *22*, 169–182 (1935).
47 Kerr K. B., Petkovich O. L.: Active immunity in rabbits to the liver fluke *Fasciola hepatica.* J. Parasit. *21*, 319–320 (1935).
48 Kowalski J. C., Thorson R. E.: Immunization of laboratory mice against tetrathyridia of *Mesocestoides corti* (Cestoda) using a secretory and excretory antigen and a soluble somatic antigen. J. Parasit. *58*, 732–734 (1972).
49 Kwa B. H., Liew F. Y.: Immunity in taeniasis – cysticercosis. I. Vaccination against *Taenia taeniaeformis* in rats using purified antigen. J. exp. Med. *146*, 118–131 (1977).
50 Lang B. Z.: Host-parasite relationships of *Fasciola hepatica* in the white mouse. VII. Effects of anti-worm incubate sera on transferred worms and successful vaccination with a crude incubate antigen. J. Parasit. *62*, 232–236 (1976).
51 Lang B. Z., Hall R. F.: Host-parasite relationships of *Fasciola hepatica* in the white mouse. VIII. Successful vaccination with culture incubate antigens and antigens from sonic disruption of immature worms. J. Parasit. *63*, 1046–1049 (1977).
52 Larsh J. E. jr.: Studies on the artificial immunization of mice against infection with dwarf tapeworm, *Hymenolepis nana var. Fraterna.* Amer. J. Hyg. *39*, 129–132 (1944).
53 Larsh J. E. jr., Goulson H. T., Weatherly N. F., Chaffee E. F.: Studies on delayed (cellular) hypersensitivity in mice injected with *Trichinella spiralis.* V. Tests in recipients injected with donor spleen cells 1,3,7, 14 or 21 days before infection. J. Parasit. *56*, 978–981 (1970).
54 Lejkina E. S.: Early immunological diagnosis of ascaridosis. In: Contributions to Helmintholology Academy of Science, U.S.S.R. p. 362–370 (1953).
55 Levine D. M., Kagan I. G.: Studies on the immunology of schistosomiasis by vaccination and passive transfer. J. Parasit. *46*, 787–792 (1960).
56 Leskowitz S., Waksman B. H.: Studies in immunization. The effect of route of infection of bovine serum albumin in Freund adjuvant on production of circulating antibody and delayed hypersensitivity. Immunology *84*, 58–71 (1960).
57 Lin S., Ritchie L. S., Hunter G. W.: Acquired immunologic resistance against *Schistosoma japonicum.* J. Parasit. *40*, (Suppl.) 42 (1954).
58 Lowry O. H., Rosebrough M. J., Lewis-Farr A., Randall R. J.: Protein measurement with the folin-phenol reagent. J. biol. Chem. *193*, 265–275 (1951).
59 Mayrhofer G., Bazin H., Gowans J. L.: Nature of cells binding anti-IgE in rats immunized with *Nippostrongylus brasiliensis:* IgE synthesis in regional nodes and concentration in mucosal mast cells. Europ. J. Immunol. *6*, 537–545 (1976).
60 McCoy O. R.: Artificial immunization of rats against *Trichinella spiralis.* Amer. J. Hyg. *21*, 200–213 (1935).
61 MacDonald E. M., Scott J. A.: Experiments on immunity in the cotton rat to the filarial worm, *Litomosoides carinii.* Exp. Parasit. *2*, 174–184 (1953).
62 Miller H. M.: Experiments on immunity of the white rat to *Cysticercus fasciolaris.* Proc. Soc. exp. Biol. (N.Y.) *27*, 926 (1930).
63 Miller H. M.: Further experiments on artificial immunity to a larval cestode. Proc. Soc. exp. Biol. (N.Y.) *28*, 884–885 (1931a).
64 Miller H. M.: The production of artificial immunity in the albino rat to a metazoan parasite. J. prevent. med. *5*, 429–452 (1931b).

65 Miller H. M.: Further studies on immunity to a metazoan parasite, *Cysticercus fasciolaris.* J. prevent. Med. *6*, 37–46 (1932).
66 Miller H. M., Kerr K. B.: Attempts to immunize rabbits against a larval cestode, *Cysticercus pisiformis.* Proc. Soc. exp. Biol. (N.Y.) *29*, 670–671 (1932).
67 Miller H. R. P., Jarrett W. F. H.: Immune reactions in mucous membranes. I. Intestinal mast cell response during helminth expulsion in the rat. Immunology *20*, 277–288 (1971).
68 Miller R. G. jr.: Simultaneous statistical interference. McGraw-Hill, New York 1966.
69 Miller T. A.: Effect of age of the dog on immunogenic efficiency of double vaccination with X-irradiated *Ancylostoma caninum* larvae. Amer. J. vet. Res. *26*, 1383–1390 (1965).
70 Mota I.: Mast cell and histamine in rat anaphylaxis: the effect of *Haemophilus pertussis.* Nature (Lond.) *182*, 1021–1022 (1958).
71 Mulligan W., Urquhart G. M., Jennings F. W., Nielsen J. T. M.: Immunological studies on *Nippostrongylus brasiliensis* infection in the rat: the "self cure" phenomenon. Exp. Parasit. *16*, 341–347 (1965).
72 Murray M., Jarrett W. F. H., Jennings F. W.: Mast cells and macromolecular leak in intestinal immunological reactions. The influence of sex of rats infected with *Nippostrongylus brasiliensis.* Immunology *21*, 17–31 (1971).
73 Murray M.: Immediate hypersensitivity effector mechanisms. II. In vivo reactions. In: Immunity to animal parasites (ed. by E. J. L. Soulsby), p. 155–190. Academic Press, New York/ London 1972.
74 Murray M.: Local immunity and its role in vaccination. Vet. Rec. *93*, 500–504 (1973).
75 Murrell K. D., Clay B.: In vitro detection of cytotoxic antibodies to *Schistosoma mansoni* schistosomules. Amer. J. trop. Med. Hyg. *21*, 569–577 (1972).
76 Murrell K. D., Dean D. A., Stafford E. E.: Resistance to infection with *Schistosoma mansoni* after immunization with worm extracts or live cercariae: role of cytotoxic antibody in mice and guinea pigs. Amer. J. trop. Med. Hyg. *24*, 955–962 (1975).
77 Nakashima I., Ohta F., Kobayashi T., Kato O., Kato N.: Effect of antigen doses and time intervals between antigen injections and secondary, tertiary and quaternary antibody response. Immunology *26*, 443–454 (1974).
78 Ogilvie Bridget M.: Reagin-like antibodies in rats infected with the nematode *Nippostrongylus brasiliensis.* Immunology *12*, 113–131 (1967).
79 Ogilvie Bridget M., Jones Valerie R.: Immunity in the parasitic relationship between helminths and hosts. Progr. Allergy *17*, 93–144 (1973).
80 Orr T. S. C., Blair A. M. J. N.: Potentiated reagin response to egg albumin and conalbumin in *Nippostrongylus brasiliensis*-infected rats. Life Sci. *8*, 1073–1077 (1969).
81 Ozawa M.: Experimental study on acquired immunity to *Schistosomiasis japonica.* Jap. J. exp. Med. *8*, 79–84 (1930).
82 Ozerol N. H., Silverman P. M.: Further characterization of active metabolites from histotropic larvae of *Haemonchus contortus* cultured in vitro. J. Parasit. *56*, 1199–1205 (1970).
83 Phillips S. M., Reid W. A., Doughty Barbara, Khoury P. B.: The cellular and humoral immune response to *Schistosoma mansoni* infections in inbred rats. III. Development of optimal protective immunity following natural infections and artificial immunizations. Cell. Immunol. *38*, 255–258 (1978).
84 Poulain J., Pery P., Luffau G.: Protection of rats against *Nippostrongylus brasiliensis* with worm antigens by oral administration. Ann. Immunol. (Inst. Pasteur) *127C*, 209–213 (1976).
85 Rhodes M. B., Nayak D. P., Kelley G. W., Marsh C. L.: Studies in helminth enzymology. IV. Immune response to malic dehydrogenase from *Ascaris suum.* Exp. Parasit. *16*, 373–381 (1965).
86 Ritchie L. S., Garson S., Erickson D. G.: Attempts to induce resistance against *Schistosoma mansoni* by injecting cercarial, adult worm and egg homogenates in sequence. J. Parasit. *48*, 233–236 (1962).

87 Rickard M. D., Bell K. J.: Successful vaccination of lambs against infection with *Taenia ovis* using antigens produced during in vitro cultivation of the larval stages. Res. vet. Sci. *12*, 401–402 (1971).
88 Rickard M. D., Adolph A. J.: Vaccination of calves against *Taenia saginata* infection using a "parasite-free" vaccine. Vet. Parasit. *1*, 389–392 (1976).
89 Rickard M. D., White J. B., Boddington E. B.: Vaccination of lambs against infection with *Taenia ovis*. Aust. vet. J. *52*, 209–214 (1976).
90 Rickard M. D., Adolph A. J., Arundel J. H.: Vaccination of calves against *Taenia saginata* infection using antigen collected during in vitro cultivation of larvae: passive protection via colostrum from vaccinated cows and vaccination of calves protected by maternal antibody. Res. vet. Sci. *23*, 365–367 (1977).
91 Rickard M. D., Boddington E. B., McQuade M.: Vaccination of lambs against *Taenia ovis* infection using antigens collected during in vitro cultivation of larvae: passive protection via colostrum from vaccinated ewes and the duration of immunity from a single vaccination. Res. vet. Sci. *23*, 368–371 (1977).
92 Robinson D. L. H.: In vitro studies on *Haemonchus contortus*. In: Problems of in vitro culture (ed. by Angela E. R. Taylor), p. 61–69. Blackwell Scientific Publications, Oxford/Edinburgh 1967.
93 Rose J. H.: Preliminary results using metabolites and in vitro grown larvae of *Ostertagia circumcincta* to immunize lambs against oral challenge. Res. vet. Sci. *21*, 76–78 (1976).
94 Rose J. H.: Further attempts to immunize lambs using metabolites and in vitro grown larvae of *Ostertagia circumcincta*. Res. vet. Sci. *24*, 61–64 (1978).
95 Ross J. G.: Studies of immunity to *Fasciola hepatica*. Acquired immunity in cattle, sheep and rabbits following natural infection and vaccine procedures. J. Helminth. *XLI*, 393–399 (1967).
96 Rothwell T. L. W., Love R. J.: Vaccination against the nematode *Trichostrongylus colubriformis*. I. Vaccination of guinea pigs with worm homogenates and soluble products released during in vitro maintenance. Int. J. Parasit. *4*, 293–299 (1974).
97 Rothwell T. L. W., Merritt G. C.: Vaccination against the nematode *Trichostrongylus colubriformis*. II. Attempts to protect guinea pigs with worm acetylcholinesterase. Int. J. Parasit. *5*, 453–460 (1975).
98 Rothwell T. L. W.: Vaccination against the nematode *Trichostrongylus colubriformis*. III. Some observations on factors influencing immunity to infection in vaccinated guinea pigs. Int. J. Parasit. *8*, 33–37 (1978).
99 Sadun E. H., Lin S. S.: Studies on the host parasite relationships to *Schistosoma japonicum*. IV. Resistance acquired by infection, by vaccination and by the injection of immune serum, in monkeys, rabbits and mice. J. Parasit. *45*, 543–548 (1959).
100 Sadun E. H.: Immunization in schistosomiasis by previous exposure to homologous and heterologous cercariae, by inoculation of preparations from schistosomes and by exposure to irradiated cercariae. Ann. New. Y. Acad. Sci. *113*, 418–439 (1963).
101 Sadun E. H., Bruce J. I.: Resistance induced in rats by previous exposure to and by vaccination with fresh homogenates of *Schistosoma mansoni*. Exp. Parasit. *15*, 32–43 (1964).
102 Scott H. L., Silverman P. M., Mansfield M. E., Levine H. S.: *Haemonchus contortus* infection in sheep: active and passive immunity in sheep given oral iron supplement. Amer. J. vet. Res. *32*, 249–262 (1971).
103 Seddon H. R.: The development in sheep of immunity to *Moniezia expansa*. Ann. trop. Med. Parasit. *125*, 431–435 (1931).
104 Sheldon A. J.: Studies on active acquired resistance, natural and artificial in the rat to infection with *Strongyloides ratti*. Amer. J. Hyg. *25*, 53–56 (1937).
105 Sher A., Kusel J. R., Perez H., Clegg J. A.: Partial isolation of a membrane antigen which induces the formation of antibodies lethal to schistosomes cultured in vitro. Clin. exp. Immunol. *18*, 357–369 (1974).

106 Shibanai D., Tozawa M., Takahashi M., Isoda M.: Experimental studies on vaccination against *Fasciola hepatica.* Bull. Azabu vet. Coll. Japan *3*, 85–86 (1956) Helminthological Abstracts, *25*, 364, 1956).
107 Silverman P. M., Paterson J. E.: Histotrophic (parasitic) stages of *Haemonchus contortus.* Nature (Lond.) *185*, 54–55 (1960).
108 Silverman P. H., Poynter D., Podger K. R.: Studies on larval antigens derived by cultivation of some parasitic nematodes in simple media: protection tests in laboratory animals. J. Parasit. *48*, 562–571 (1962).
109 Soulsby E. J. L.: Immunization against *Ascaris lumbricoides* in the guinea pig. Nature (Lond.) *179*, 783–784 (1957).
110 Soulsby E. J. L.: The nature and origin of the functional antigens in helminth infections. Ann. N. Y. Acad. Sci. *113*, 492–509 (1963).
111 Spencer J. C., Waldman R. M., Johnson J. E.: Local and systemic cell-mediated immunity after immunization of guinea pigs with live or killed *M. tuberculosis* by various routes. J. Immunol. *112*, 1322–1328 (1974).
112 Steinberg P., Ishizaka K., Norman P. S.: Possible role of IgE-mediated reaction in immunity. J. Allergy clin. Immunol. *54*, 359–366 (1974).
113 Stromberg B. E., Soulsby E. J. L.: *Ascaris suum.* Immunization with soluble antigens in the guinea pig. Int. J. Parasit. *7*, 287–291 (1977).
114 Thompson J. H.: Host-parasite relationships of *Schistosoma mansoni.* Exp. Parasit. *13*, 140–160 (1954).
115 Thorson R. E.: The relation of the secretions and excretions of the larvae of *Nippostrongylus muris* to the production of protective antibodies. J. Parasit. *37*(Suppl.), 18–19 (1951).
116 Thorson R. E.: Studies on the mechanism of immunity in the rat to the nematode, *Nippostrongylus muris.* Amer. J. Hyg. *58*, 1–15 (1953).
117 Thorson R. E.: The stimulation of acquired immunity in dogs by injections of extracts of the oesophagus of adult hookworms. J. Parasit. *42*, 501–504 (1956).
118 Turner E. L., Berberian D. A., Dennis E. W.: Successful artificial immunization of dogs against *Taenia echinococcus.* Proc. Soc. exp. Biol. (N.Y.) *30*, 618–619 (1932/33).
119 Turner E. L., Berberian D. A., Dennis E. W.: The production of artificial immunity in dogs against *Ecchinococcus granulosus.* J. Parasit. *22*, 14–28 (1936).
120 Urquhart G. M., Mulligan W., Jennings F. W.: Artificial immunity to *Fasciola hepatica* in rabbits. I. Some studies with protein antigens of *F. hepatica.* J. infect. Dis. *94*, 126–133 (1954).
121 Urquhart G. M., Jarrett W. F. H., Mulligan W.: Helminth immunity. In: Advances in veterinary sciences (ed. by C. A. Brandley and E. J. Jungler), vol. 7, p. 87–129. Academic Press, New York/London 1962.
122 Van Zandt P. D.: Immunity relationships in white mice infected with *Nematospiroides dubius* Baylis, 1926 (Nematoda: Meligmosomidae). II. Artificial immunization with antigen prepared from larvae. J. Parasit. *48*, 249–252 (1962).
123 Varga J.: Immunization experiments with irradiated larvae of *Syngamus trachea* in chickens. Isotopes Radiation Parasitology, Panel Proceedings Series, p. 1–11. International Atomic Energy Agency, Vienna 1968.
124 Vernes A.: Immunization of the mouse and minipig against *Trichinella spiralis.* In: Biochemistry of parasites and host-parasite relationships (ed. by H. van de Bossche), p. 319–324. Elsevier/North-Holland/Biomedical Press, Amsterdam 1976.
125 Vogel H., Minning W.: Über die erworbene Resistenz von *Macacus rhesus* gegenüber *Schistosoma japonicum.* Z. Tropenmed. Parasit. *4*, 418–505 (1952/53).
126 Wade A. E., Swanson L. E., Fox L. A.: Studies on infection and immunity with the lungworm, *Dictyocaulus viviparus* (Bloch). I. Active immunization of guinea pigs and rabbits. Amer. J. vet. Res. *22*, 123–127 (1961).

127 Wade A. E., Swanson L. E., Fox L. E., Simpson C. F., Malewitz T. D.: Studies on infection and immunity with lungworm, *Dictyocaulus viviparus* (Bloch). II. Active immunization of calves. Amer. J. vet. Res. *23*, 277–283 (1962).
128 Wakelin D., Selby Gwendoline R.: Functional antigens of *Trichuris muris*. The stimulation of immunity by vaccination of mice with somatic antigen preparations. Int. J. Parasit. *3*, 711–715 (1973).
129 Waldman R. M., Ganguly R.: Cell-mediated immunity and the local immune system. In: The immune system and infectious diseases (ed. by E. Neter and F. Milgrom), p. 334–346. Karger, Basel 1975.
130 Watt J. T. C.: Active immunization of rats against *Nippostrongylus muris*. Proc. Soc. exp. Biol. (N.Y.) *52*, 67–72 (1943).
131 Watts N. P.: Prophylactic use of schistosomal antigen. J. Immunol. *62*, 183–192 (1949).
132 World Health Organisation: Immunological adjuvants. Techn. Rep. Ser. No. 595. WHO, Geneva 1976.