Polyamine metabolism in a member of the phylum Microspora (Encephalitozoon cuniculi): effects of polyamine analogues

Cyrus J. Bacchi,1 Donna Rattendi,1 Evangeline Faciane,1 Nigel Yarlett,1,2 Louis M. Weiss,3 Benjamin Frydman,4 Patrick Woster,5 Benjamin Wei,5 Laurence J. Marton4 and Murray Wittner3

Correspondence
Cyrus J. Bacchi
cbacchi@pace.edu

1,2Haskins Laboratories and Departments of Biology1 and Chemistry2, Pace University, New York, NY 10038, USA
3Departments of Medicine and Pathology, Albert Einstein College of Medicine, Bronx, NY 10461, USA
4SLIL Biomedical Corp., Madison, WI 53711, USA
5Department of Pharmaceutical Sciences, College of Pharmacy and Health Sciences, Wayne State University, Detroit, MI 48202, USA

The uptake, biosynthesis and catabolism of polyamines in the microsporidian parasite Encephalitozoon cuniculi are detailed with reference to the effects of oligoamine and arylamine analogues of polyamines. Enc. cuniculi, an intracellular parasite of mammalian cells, has both biosynthetic and catabolic enzymes of polyamine metabolism, as demonstrated in cell-free extracts of mature spores. The uptake of polyamines was measured in immature, pre-emergent spores isolated from host cells by Percoll gradient. Spermine was rapidly taken up and metabolized to spermidine and an unknown, possibly acetamidopropanal, by spermidine/spermine N1-acetyltransferase (SSAT) and polyamine oxidase (PAO). Most of the spermidine and the unknown product were found in the cell incubation medium, indicating they were released from the cell. bis(Ethyl) oligoamine analogues of polyamines, such as SL-11144 and SL-11158, as well as arylamine analogues [BW-1, a bis(phenylbenzyl) 3-7-3 analogue] blocked uptake and interconversion of spermine at micromolar levels and, in the case of BW-1, acted as substrate for PAO. The Enc. cuniculi PAO activity differed from that found in mammalian cells with respect to pH optimum, substrate specificity and sensitivity to known PAO inhibitors. SL-11158 inhibited SSAT activity with a mixed type of inhibition in which the analogue had a 70-fold higher affinity for the enzyme than the natural substrate, spermine. The interest in Enc. cuniculi polyamine metabolism and the biochemical effects of these polyamine analogues is warranted since they cure model infections of Enc. cuniculi in mice and are potential candidates for human clinical trials.

INTRODUCTION

The microsporidia are a group of obligate intracellular parasites of the phylum Microspora. With over 144 genera and 1200 species, these organisms parasitize a wide range of hosts from insects to fish, non-primate mammals and man (Wittner & Weiss, 1999). Microsporidia are true eukaryotes containing a nucleus, nuclear membrane, intracytoplasmic membrane system, a Golgi apparatus, and chromosome separation on mitotic spindles. No mitochondria or centrioles are present. Microsporidia form characteristic unicellular spores which extrude a polar tube through which sporoplasm is passed to inoculate a host cell (Wittner & Weiss, 1999). Little is known concerning the metabolism of the microsporidia, except for a few studies identifying glycolytic enzymes and metabolites which are excystment requirements (Weidner et al., 1999). Molecular studies have recently characterized RNA and the full genome sequence of Encephalitozoon (Enc.) cuniculi is now known (Wittner & Weiss, 1999; Katinka et al., 2001).

Abbreviations: AdoMetdc, S-adenosylmethionine decarboxylase; DFMO, DL-a-difluoromethylornithine hydrochloride; ODC, ornithine decarboxylase; PAO, polyamine oxidase; SSAT, spermidine/spermine N1-acetyltransferase.
The microsporidia have become increasingly important as human pathogens in AIDS. There are approximately eight genera with species proven to be pathogenic in humans. *Enterocytozoon* (*Ent.*) *biuni*, an enteric parasite which causes intractable diarrhoea in AIDS, is the most common species (Wittner & Weiss, 1999; Weber et al., 1994).

Chemotherapy for microsporidia infections has relied on the benzimidazoles and fumagillin, which are generally effective with exceptions: albendazole is not effective versus *Ent. biuni* and fumagillin has cytotoxic effects, especially in AIDS patients (Didier, 1997; Costa & Weiss, 2000; Dieerich et al., 1994; Weiss et al., 1994a; Katiyar et al., 1994).

With this as background, our work has focused on polyamine metabolism in the microsporidia using *Enc. cuniculi* as model organism (Bacchi et al., 2001). Polyamines are low-molecular-mass polycations, found universally in cells, which function as cofactors for macromolecule synthesis, in osmotic control, and as structural facilitators for nucleic acids (Cohen, 1998). The major polyamines are putrescine, spermidine and spermine. Polyamines are absolutely required for cell division and differentiation and their internal concentrations are carefully controlled by synthesis, degradation, excretion and uptake from the environment. In mammals and many protozoa, synthesis occurs from the conversion of ornithine to putrescine through ornithine decarboxylase (ODC) (Bacchi & Yarlett, 2002), although the enteric parasite *Cryptosporidium parvum* has a plant-like pathway in which arginine is the starting point for putrescine synthesis through arginine decarboxylase (Keithly et al., 1997). One or two aminopropyl groups, originating from decarboxylated S-adenosylmethionine, are added to putrescine to form spermidine and spermine, respectively. The limiting enzymes of polyamine synthesis are ODC and S-adenosylmethionine decarboxylase (AdoMetdc), both of which are highly inducible and have short half-lives in the cell (Marton & Pegg, 1995). Mammalian cells, as well as some protozoa, take up spermidine and spermine, interconverting them to spermidine and putrescine, respectively. The key enzymes in interconversion are spermidine/spermine N\(^1\)-acyltransferase (SSAT) and polyamine oxidase (PAO). SSAT is also highly inducible by exogenous polyamines, and the trio of ODC, AdoMetdc and SSAT serves to keep intracellular polyamines at relatively stable levels (Marton & Pegg, 1995).

Chemotherapeutic interest in the polyamine pathway was initially spurred by the development of enzyme-activated inhibitors of ODC [DL-\(\alpha\)-difluoromethylornithine hydrochloride (DFMO)] and AdoMetdc (MDL 73811, AbeAdo; Bacchi & Yarlett, 2002). Although these were not effective clinically as anti-tumour agents, DFMO found use clinically against African sleeping sickness (Schechter & Sjordamsa, 1989) and AbeAdo in experimental trypanosome infections (Bitonti et al., 1990). More recent attention, however, has focused on polyamine analogues such as bis(ethyl)norspermine (BE 3-3-3) and bis(ethyl)homospermine (BE 4-4-4) as anti-tumour agents. These agents are taken into mammalian cells on polyamine transporters and down-regulate ODC and AdoMetdc, while up-regulating SSAT. The net result is that polyamine synthesis is shut down while remaining intracellular polyamines are acetylated and excreted. The resulting decline in polyamine levels causes apoptosis and cell death, since the analogues do not substitute functionally for natural polyamines (Marton & Pegg, 1995; Casero & Woster, 2001; Frydman & Valasinas, 1999; Bernacki et al., 1995).

Our recent work has demonstrated that several classes of polyamine analogues block in vitro growth of *Enc. cuniculi* and stabilize host monolayers at micromolar levels. These agents also cured well-validated laboratory model infections of *Enc. cuniculi* (Zou et al., 2001; Bacchi et al., 2002). In the present study, we examine these analogues for effects on polyamine metabolism in *Enc. cuniculi*.

**METHODS**

**Strain and growth conditions.** *Enc. cuniculi* was obtained from Dr Ann Cali of Rutgers University. It was cultivated in RK-13 (rabbit kidney) or HEK (human embryonic kidney, ATCC CRL-1573) cells. Cells were grown to 80% confluency in Falcon T-75 flasks (Becton-Dickinson) at 37 °C in 5% CO\(_2\)/air, and infected with 5 \(\times\)10\(^5\) spores. Infected monolayers were also trypsinized and split into additional flasks. After 1 week of culture, greater than 50% infectivity was obtained. The medium used was Minimal Eagle's Medium, Earle's salts, l-glutamine, 7% (w/v) fetal bovine or newborn calf serum (Visvesvara et al., 1991). The medium was changed twice (RK-15 cells) or three times (HEK cells) weekly, and the old medium containing mature spores was pooled and aseptically stored at 4 °C.

**Enzyme preparations.** Intact mature spores were obtained from supernatant culture media and stored aseptically at 0–4 °C (Bacchi et al., 2001). Spores were washed in 150 mM PBS [0.9% (w/v) NaCl] containing 1% (w/v) SDS and resuspended in PBS prior to breaking. Spores were poured into 2 ml microfuge tubes containing 425–600 nm glass beads (Sigma) and disrupted (6–8 min at 4 °C) using a Mini Bead Beater (Bio Spec Products) or Vortex Mixer and adapter (#13000-50-V1; Mo Bio Laboratories) (Weiss et al., 1994b). Homogenate preparations with greater than 90% breakage (by microscopy) were collected and cleared by centrifugation at 2200 g for 10 min. The cleared supernatants were used to determine SSAT and PAO activity.

**Gradient purification of pre-emergent spores.** The large-scale procedure described previously (Bacchi et al., 2001) was used to obtain purified preparations of pre-emergent spores. Usually 10 heavily infected (50–80%) monolayers from Falcon T75 flasks were trypsinized, harvested and ground in a glass vessel for 6–8 min (3–4 × 2 min grinding) at 0–4 °C. The breakage medium contained W-T medium (described below under ‘Incubation studies using pre-emergent spores’) plus a protease inhibitor cocktail containing 2.7 mM *N*-p-tosyl-l-lysine chloromethyl ketone hydrochloride (TLCK), 0.15 mM aprotinin, 2.2 mM leupeptin and 0.5 mM DTT in 50 mM KC1/0.15 M Na\(_2\)PO\(_4\), pH 7.4. Cell homogenates were passed through 12 μm and 5 μm filters and the final filtrate was centrifuged for 10 min at 15 000 g on 50% (v/v) stock isotonic Percoll (1 ml/11 ml Beckman 14 × 89 mm tube; Green et al., 1999). Two bands were obtained, a broad one at 1.018–1.035 g ml\(^{-1}\) (light band) and a narrower one at 1.102–1.119 g ml\(^{-1}\) (heavy band). We had demonstrated from the previous study that the heavy band...
contained pre-emergent spores and immature spores while the light band contained debris, spore cases and some immature stages (Bacchi et al., 2001). Since the heavy fraction exhibited far greater metabolic activity than the light fraction (Bacchi et al., 2001), we used it for the data presented in the present study. Cell counts of suspensions in several experiments prior to and post-incubation indicated that no lysis of these forms had occurred.

Polymine analysis. Polymine content was quantified by reversed-phase HPLC using a Perkin-Elmer LC-410 pump and a pcosphere C18 5 µ 150 x 6.6 mm column (Perkin Elmer). Heavy gradient fractions (pre-emergent spores) were extracted with 10% (w/v) trichloroacetic acid (TCA) at 0–4 °C. Denatured protein was removed by centrifugation and extracts were pre-column derivatized with 0.8 g o-phthalaldehyde l⁻¹ (2:1) dissolved in 3 ml methanol added to 30-9 g boric acid l⁻¹ containing 24 g KOH l⁻¹ (pH 10–4). The derivatized samples were quantified with a Perkin-Elmer LC 240 fluorescence detector using an excitation wavelength of 320 nm and an absorption wavelength of 455 nm. Signals were integrated using β-ram (IN/US Systems) Version 3.1 software. Concentrations of polymines were determined relative to standards. The HPLC solvent gradient used and other details have been described previously (Yarlett et al., 1994).

Enzyme assays. All incubations were at 37 °C. SSAT was measured according to Libby et al. (1989) in a reaction containing 0:06 M Bicine buffer (pH 8-0), 0.15–6 mM spermine or spermidine, 0.1 µCi (0.5 nmol) [L-14C]acetyl-CoA and 50 µl spore enzyme preparation. Reactions were incubated for 30 min, stopped by addition of 20 µl 0.5 M hydroxylamine, and placed on ice. Reaction tubes were heated for 3 min in a boiling water bath and centrifuged to remove protein. Clarified reactions were spotted on P-81 phosphocellulose filters. Filters were washed with distilled water, then methanol, dried and counted. Activity is expressed as nmol (mg protein)⁻¹ (30 min)⁻¹.

PAO was measured spectrophotometrically (Beckman DU 640) according to the method of Childs & Bardsley (1975) in 0-1 M glycine buffer (pH 7-0) containing 10 units of horseradish peroxidase [Sigma Type VIA: 1 unit will oxidize 1 nmol 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) min⁻¹] and 50 µl spore enzyme preparation. Reactions were incubated for 30 min, stopped by addition of 20 µl 5 M hydroxylamine, and placed on ice. Reaction tubes were heated for 3 min in a boiling water bath and centrifuged to remove protein. Clarified reactions were spotted on P-81 phosphocellulose filters. Filters were washed with distilled water, then methanol, dried and counted. Activity is expressed as nmol (mg protein)⁻¹ (30 min)⁻¹.

Incubation studies using pre-emergent spores. The effect of polymine analogues on polymine synthesis and interconversion was examined on intact pre-emergent spores. Heavy gradient preparations were incubated in W-T medium. Polymine analogues and radiolabelled substrates were added at the start of the 1 or 2 h incubation period. After incubation, preparations were centrifuged at 12000 g for 10 min, and pellets were washed in incubation medium and lysed with 250 µl of 10% (w/v) TCA. Lysates were kept at 0–4 °C overnight and frozen until analysis. Supernatants from incubations were aspirated from pellets and frozen until analysis. All incubations were done in duplicate.

HPLC analysis. Lysates and supernatant incubation media from incubations of intact pre-emergent spores with L-[2,3-14C]homithine or [L-14C]spermine were analysed by HPLC using procedures outlined previously (Bacchi et al., 2001). An IN/US flow-through radio-detector monitored radioactivity and the IN/US β-2 RAM software package (IN/US Systems) was used for data peak integration. Using this system, we obtained the following retention times, based on radiolabelled standards: ornithine, 12 min; putrescine, 24 min; spermidine, 28 min; spermine, 31 min. Acetamidopropionaldehyde had a retention time of 3.5 min, based on UV absorption analysis.

Uptake studies. Pre-emergent spore preparations were incubated for 15 min in duplicate with varying concentrations of [1–4 terminal methylene-14C]spermine, [terminal methylene-H(N)]spermidine [1,4-14C]putrescine or L-[2,3-14C]homithine. The W-T incubation medium was used, with 0.2 ml reaction mixtures centrifuged through 0.2 ml mineral oil at 12,000 g for 0.5 min. Aqueous and oil layers were aspirated, and the tips of microfuge tubes were cut off and analysed by liquid scintillation counting in the presence of Beckman Ready Protein scintillation fluor (Beckman Instruments) as in Goldberg et al. (1998).

Protein determination. Protein content was estimated by the Bradford method, using BSA as standard.

Chemicals. Radiolabelled chemicals were purchased as follows: [1–4 terminal methylene-14C]spermine (113 mCi mmol⁻¹; 4.18 GBq mmol⁻¹), Amersham Pharmacia Biotech; L-[2,3-14C]homithine (40 mCi mmol⁻¹; 1.48 GBq mmol⁻¹), Moravek Biochemicals; [1-14C]acetlyl-CoA (35 mCi mmol⁻¹; 2.2 GBq mmol⁻¹); [terminal methylene-2H(N)]spermidine (25 mCi mmol⁻¹; 93 GBq mmol⁻¹); [1,4–14C]putrescine (110 mCi mmol⁻¹; 4.07 GBq mmol⁻¹), NEN Life Science Products.

Polyamine analogues were obtained as follows: SL-11061 (BE 4 x 4), SL-11093, SL-11144, SL-11158, Dr Benjamin Fryzman, SLIL Bio-medical (synthesis: Valasinas et al., 2001; Bacchi et al., 2002); BW-1, Dr Patrick Woster, Wayne State University (synthesis: Zou et al., 2001). MDL 72521, MDL 72527, MDL 27695, DFMO and difluoro-methylarginine were gifts from Marion Merrell Dow. Other chemicals were obtained from Sigma.

RESULTS

Polymine content of pre-emergent spores

Heavy gradient fractions were analysed by HPLC and fluorescence detection for polymine content after isolation and washing. Analysis of seven separate preparations yielded a mean of 38.15 ± 27.8 nmol (mg protein)⁻¹ for spermine and 23 ± 15.8 nmol (mg protein)⁻¹ for spermidine. Neither putrescine nor cadaverine were found using techniques sensitive to 50 pmol per sample (Yarlett et al., 1994). We had earlier reported polymine content of mature, released spores to include low levels of putrescine as compared to spermidine and spermine (Coyle et al., 1996).
Table 1. Activities of enzymes of polyamine metabolism in freshly isolated mature spores of *Enc. cuniculi*

Spores were obtained aseptically from supernatants of infected HEK or RK-13 cells. Enzyme preparations were made using glass beads as described in Methods. Data are the mean of (n) 4–13 preparations, assayed in duplicate. Ranges are in parentheses. Data for ODC, arginine decarboxylase (ADC) and AdoMetdc were previously reported by Bacchi et al. (2001) and included for comparative purposes.

Enzymes of polyamine metabolism

Mature spores were broken using the beadbeater technique (Weiss et al., 1994b), clarified by centrifugation and, used as cell-free extracts, assayed for SSAT and PAO, enzymes of polyamine degradation. Results in Table 1 are compared to previously reported data for the synthetic enzymes ODC, SSAT and AdoMetdc (Bacchi et al., 2001). PAO is four times more active than AdoMetdc and >17-fold more active than ODC. Spermine was the preferred substrate for SSAT, while N\textsuperscript{6}-acetyl spermine was the most active substrate for PAO. Other activity/inhibitor data for SSAT and for PAO are given under ‘Effects of polyamine analogues on polyamine metabolism of pre-emergent spore preparations’. Arginine decarboxylase activity was less than 0.0036 nmol (mg protein)\textsuperscript{-1} (2 h)\textsuperscript{-1} – below the lower limit of detection for the assay. This activity was not inhibitable by difluoro-methylarginine (DFMA), a specific inhibitor of the enzyme (Bitonti et al., 1982). Likewise, DFMA was not an inhibitor of ODC, while DFMO at 1 mM was 55% inhibitory (Bacchi et al., 2001).

Polyamine synthesis and uptake by heavy gradient fractions

We had initially examined polyamine metabolism in mature spores freshly isolated from supernatant culture media, but found this activity to be very low (Bacchi et al., 2001). Early studies on polyamine metabolism in pre-emergent spores used both heavy and light gradient fractions incubated in 150 mM Na\textsubscript{3}PO\textsubscript{4}-buffered 0.8% (w/v) NaCl, yielding wide-ranging results (Bacchi et al., 2001). Nevertheless, these data indicated that uptake and conversion of L-[2,3-\textsuperscript{3}H]ornithine +500 \mu\text{M} L-methionine to putrescine, spermidine and spermine occurred at about 12% of the rate of interconversion of L-[\textsuperscript{14}C]spermidine and putrescine [55.4 nmol (mg protein)\textsuperscript{-1} (2 h)\textsuperscript{-1}, 12 preparations, versus 444.8 nmol (mg protein)\textsuperscript{-1} (2 h)\textsuperscript{-1}, 9 preparations, respectively; Bacchi et al., 2001].

We also examined uptake of polyamines in pre-emergent spores to compare rates of uptake. Table 2 lists \( K_m \) and \( V_{max} \) values of an experiment in which pre-emergent spores were examined in a rapid uptake study. Incubation mixtures (0.2 ml) containing increasing concentrations of radiolabelled ornithine, putrescine, spermidine and spermine were centrifuged through 0.2 ml mineral oil at 12 000 \text{g}. Incubations of 15 min were used in a procedure we have used for uptake studies with African trypanosomes and obtained negligible carry-over of exogenous label (Goldberg et al., 1998). Table 2 shows that, of the four molecules studied, spermine had the lowest \( K_m \) value (12.5 nmol) and the highest \( V_{max} \) [10 000 nmol (15 min)\textsuperscript{-1}]. One gauge of

<table>
<thead>
<tr>
<th>Enzyme</th>
<th>Substrate</th>
<th>n</th>
<th>Activity [nmol (mg protein)\textsuperscript{-1} (2 h)\textsuperscript{-1}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ODC</td>
<td>1-[\textsuperscript{14}C]Ornithine</td>
<td>4</td>
<td>25-35 (18-6–32-1)</td>
</tr>
<tr>
<td>ADC</td>
<td>[U-\textsuperscript{14}C]Arginine</td>
<td>4</td>
<td>&lt;0-0036</td>
</tr>
<tr>
<td>AdoMetdc</td>
<td>$[\textsuperscript{14}C]\text{AdoMet} $</td>
<td>4</td>
<td>123-6 (28-6–242-3)</td>
</tr>
<tr>
<td>SSAT</td>
<td>[1-\textsuperscript{14}C]Acetyl-CoA</td>
<td>13</td>
<td>24-12 (5-6–52-8)</td>
</tr>
<tr>
<td>PAO</td>
<td>N\textsuperscript{6}-Acetyl spermine</td>
<td>5</td>
<td>438-15 (81-02–818-3)</td>
</tr>
</tbody>
</table>

Table 2. Polyamine and amino acid uptake by *Enc. cuniculi* pre-emergent spores

Organisms were harvested from HEK cells as described. The spore suspension (240 \mu\text{g} protein) was incubated in W-T medium for 15 min with 25–500 \mu\text{M} of L-[\textsuperscript{14}C]spermine, \text{[terminal methylenes-3\textsuperscript{3}H(N)]} spermidine, \text{[1,4-\textsuperscript{14}C]}putrescine or L-[2,3-\textsuperscript{3}H]ornithine. Cells were centrifuged through 200 \mu\text{l} mineral oil; the supernatant medium was aspirated. Tips of tubes were cut off and counted in Beckman Ready Protein. Michaelis–Menten kinetics were used to analyse data.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>( K_m ) (nmol)</th>
<th>( V_{max} ) [nmol (15 min)\textsuperscript{-1}]</th>
<th>( V_{max}/K_m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-[\textsuperscript{14}C]spermine</td>
<td>12.5</td>
<td>10 000</td>
<td>800</td>
</tr>
<tr>
<td>\text{[terminal methylenes-3\textsuperscript{3}H(N)]} spermidine</td>
<td>90</td>
<td>660</td>
<td>7.3</td>
</tr>
<tr>
<td>L-[1,4-\textsuperscript{14}C]}putrescine</td>
<td>285</td>
<td>2 220</td>
<td>7.7</td>
</tr>
<tr>
<td>L-[2,3-\textsuperscript{3}H]}ornithine</td>
<td>250</td>
<td>1 810</td>
<td>7.2</td>
</tr>
</tbody>
</table>
the efficacy of transport is the $V_{\text{max}}/K_{m}$ ratio. For spermine, this ratio was 800, which was $>100$-fold higher than ratios obtained with data from other substrates. Other preparations yielded similar results.

In a series of experiments, we also examined the effects of various ionophores and ion channel reagents on spermine uptake. Used at 10–100 μM, gramicidin S, amiloride, nifedipine, nitrendipine, monensin. At 100 μM, valinomycin was 57% inhibitory (two determinations: range 10–100 μM) while KCN was 31% inhibitory and sodium azide was not inhibitory.

**Effects of polyamine analogues on polyamine metabolism of pre-emergent spore preparations**

In recent work, we had demonstrated that polyamine analogues having a backbone of repeating N-butyl subunits, such as pentamines, oligoamines or bis(aryl)-substituted 3-7-3 analogues (Fig. 1), sterilized *Enc. cuniculi*-infected monolayer cells and cured two murine model infections (Bacchi et al., 2002). We began mechanistic studies with some of the compounds that proved to be active *in vivo*, incubating pre-emergent spore preparations with 8 μM (0.25 μCi) [1-14C] spermine for 1 or 2 h, and examining the resulting 10% TCA extracts by HPLC and radiodetection for reduction in uptake and interference with spermine interconversion. In an initial series of three experiments, we found that 10 μM SL-11144 and SL-11158 inhibited spermine uptake by 66% (59–77%) and 63% (32–89%), respectively. With 0.25 μCi [terminal methylenes-3H(N)]-spermidine as substrate, SL-11144 also inhibited uptake 88.5% (single preparation) and SL-11158 58.8% (48–68.9%; two preparations) (data not shown).

In the course of these studies, we found a peak appearing at 3–5 min, which did not correspond to known polyamine standards or N3-acetyl spermine. The peak did, however, correspond to acetamidopropionaldehyde, a byproduct of polyamine interconversion which is excreted from cells (Marton & Pegg, 1995). The confirmation of the identity of this peak, however, awaits MS analysis.

In several experiments, we examined the effects of polyamine analogues on overall spermine uptake, and production of spermidine and acetamidopropionaldehyde. Table 3 gives results of a typical experiment (duplicate incubations) using the analogues SL-11061, SL-11158 and BW-1. In this experiment, we monitored internal (pellet) as well as external (supernatant medium) concentrations of spermine and products. All three analogues caused significant (70–80%) reduction in total spermine uptake, and higher inhibition of spermidine (82–95%) and acetamidopropionaldehyde (76–92%) production. SL-11061 had somewhat lower inhibition of total uptake (69.3%) as well as lower inhibition of spermidine (82.6%) and acetamidopropionaldehyde (76.3%) production. BW-1, although having a median effect on total uptake (73.4%), inhibited production of both metabolites $\geq 90%$. Although little spermidine was found as excretion product, acetamidopropionaldehyde was present in control incubations, and was reduced in SL-11158 (20%) and BW-1 (27%) supernatants. If incubations continued for 2 h, supernatant media of analogue-treated cells had 3-2 to 11.5-fold more spermine remaining in the medium than controls incubated without analogues (not shown), indicating that less uptake was occurring in these cells.

**Effects of SL-11158 on Enc. cuniculi SSAT.** The key enzyme involved in polyamine interconversion is SSAT which in *Enc. cuniculi* has two to three times the activity with spermine rather than spermidine as substrate. In mammalian cells, SSAT has a short (15 min) $t_{1/2}$ and is highly inducible (to 1000-fold, or 1% of total cell protein; Casero & Pegg, 1993).

To determine the effect of SL-11158 on enzyme kinetics of *Enc. cuniculi* SSAT, we measured enzyme activity in the presence of none, 0.54 and 1.08 mM SL-11158 with increasing concentrations of spermine (2.7, 5.4 and 10.8 mM). Incubations contained 100 μM Bicine buffer, pH 8.0, 17 μM (60 μCi mmol$^{-1}$) [1-14C] acetyl-CoA, inhibitor and spermine and 114 μg *Enc. cuniculi* spore protein preparation. After 30 min, reactions (in triplicate) were spotted on filter paper discs, washed and counted in Ominfluor. Blank reactions without spermine and protein were also run and subtracted. Results were analysed using a Hanes–Woolf primary plot ($V/[S]$ versus substrate concentration). A $K_{m}$ value of 17.3 mM was obtained for
spermine and a $K_i$ value of 0.24 mM was obtained for SL-11158 from a secondary Hanes–Woollf plot of $K_m$ versus inhibitor concentration (Fig. 2). This is a mixed type of inhibition in which the inhibitor has an affinity for the enzyme which is much higher than that of the substrate.

**Inhibitor/substrate studies on *Enc. cuniculi* PAO.** We examined a number of compounds as substrates or inhibitors of *Enc. cuniculi* PAO, and compared them to findings in the literature for mammalian PAO (Table 4). None of the compounds, used at the concentrations indicated, affected the commercial horseradish peroxidase reaction in control reactions with H$_2$O$_2$ as substrate, without N$^4$-acetylspermine and homogenate.

*Enc. cuniculi* PAO utilized N$^1$-acetylspermine and N$^6$-acetylspermidine as substrate. It did not utilize spermine, spermidine or bis(benzyl)putrescine. Unfortunately, neither N$^1$- or N$^6$-acetylspermidine nor N$^4$,$N^6$-diacetylspermine were available for study with the *Enc. cuniculi* PAO, but both are substrates for mammalian PAO. In contrast, mammalian PAO utilizes spermine N$^1$- but not N$^6$-acetylspermidine, and uses bis(benzyl)putrescine. MDL 27695 is a bis(benzyl) 3-7-3 polyamine analogue which is debenzylated by mammalian PAO (Bitonti et al., 1990), and which is also used as substrate by the *Enc. cuniculi* PAO. Aminoguanidine was not a substrate for mammalian enzyme but, at concentrations below 100 mM, was a substrate for *Enc. cuniculi* enzyme.

The pH optima of the enzymes also differed: pH 10.0 for mammalian PAO and pH 7.0–8.0 for the protozoan enzyme (Table 4). FAD superadded to control reaction mixtures did not stimulate the rate of the *Enc. cuniculi* enzyme. Two enzyme-activated irreversible inhibitors of mammalian PAO were developed by Merrell Dow Research Laboratories, MDL 72521 and MDL 72527 (Bey et al., 1985). These exhibited time- and dose-dependent kinetics and had $K_i$ values of 0.1–0.3 μM for the mammalian enzyme (Seiler, 1987). These analogues, used at up to 100 μM, stimulated the *Enc. cuniculi* enzyme by up to 70% (Table 5).

Table 5 lists activities of polyamine analogues used in this study as substrates or as inhibitors of *Enc. cuniculi* PAO.

![Fig. 2. Hanes–Woollf plot of *Enc. cuniculi* SSAT activity with spermine as substrate versus SL-11158 as inhibitor. Inhibitor concentrations: ▼, none; ▲, 0.54 mM; ○, 1.08 mM. Spermine concentrations were 2.1, 5.4 and 10.8 mM. The non-converging lines show a mixed type of inhibition. The $K_m$ value for spermine was 17.3 mM and the $K_i$ value of 0.24 mM was obtained for SL-11158. Reactions were in triplicate.](image-url)
Substrate studies were done without $N^1$-acetylspermine in the reaction, while inhibitor studies had 1 mM $N^1$-acetylspermine as substrate. Activities were determined in duplicate and corrected with blanks run with extract without $N^1$-acetylspermine. None of the compounds affected rates with H$_2$O$_2$ as substrate for horseradish peroxidase.

None of the SLIL amine analogues studied (SL-11061, SL-11093, SL-11144, SL-11158) served as substrate for the Enc. cuniculi PAO at 100 μM, and only SL-11144 and SL-11158 were significant inhibitors of the reaction at 100 μM (75 and 57 %, respectively). MDL 27695 (1 mM) was a substrate, having 34 % of the activity with the natural substrate, while BW-1 (1 mM), a bis(phenylbenzyl) 3-7-3 analogue of MDL 27695, had 55 % of control activity, and stimulated the control reaction (with $N^1$-acetylspermine as substrate) by 40 %. Pargyline is an inhibitor of monoamine oxidases, but inhibited the full reaction by 80 % and did not affect the mammalian enzyme (Table 5). These analogues did not affect the horseradish peroxidase reaction with H$_2$O$_2$ as substrate.

**DISCUSSION**

Although the microsporidia have been studied as unusual eukaryotic intracellular parasites for many years, little is known regarding their metabolism. Weidner et al. (1999) summarized the metabolic capabilities of Ameson michaelis, a parasite of the blue crab, indicating glycolysis proceeded in isolated sporoplasms when exposed to exogenous glucose and ATP. Related studies (Dolgikh et al., 1997) indicated at least eight glycolytic enzymes (but not hexokinase) were present in spores of Nosema grylli, and concluded that it is likely that glycolytically produced NADH is recycled through a glycerol-3-phosphate dehydrogenase, since other glycolytic dehydrogenases were not detectable. Since hexokinase was also not detectable in several studies, it was postulated that the microsporidia may utilize hexose phosphates directly from the host (summarized in Weidner et al., 1999).

Similarly, the ability of Enc. cuniculi to take up spermine and convert it to spermidine and putrescine, coupled with the high efficacy of spermine uptake as opposed to other polyamines or precursors, makes it likely that this microsporidian utilizes polyamine salvaged from the host cell as a major mechanism of acquiring polyamines. The kinetics of transport indicate it is used by Enc. cuniculi to scavenge any available polyamines from the host cytoplasm. Other protozoan parasites such as Trypanosoma cruzi and Trichomonas vaginalis are also believed to obtain most of their polyamines via exogenous sources (Le Quesne & Fairlamb, 1996; Ariyanayagam & Fairlamb, 1997; Yarlett et al., 1994). Since spermine uptake was not blocked by monensin, gamicidin S, ouabain or amiloride, but was inhibited by valinomycin, it appears that Na$^+$/K$^+$ ATPase was not involved in uptake, but a universal cation transporter may be responsible. Relatively low inhibition (31 %) of transport obtained with KCN reinforces the
finding that the microsporidia have neither mitochondria nor a functional cytochrome system (Undeen, 1990).

The high activity of exogenous spermine uptake in pre-emergent spores, and the increasing focus on polyamine analogues as anti-tumour agents (Casero & Woster, 2001; Frydman & Valasinas, 1999), made it imperative that we examine analogues as anti-microsporidial agents (Bacchi et al., 2002). In mammalian cells, these are taken up through polyamine transporters and down-regulate polyamine synthesis while inducing SSAT and promoting excretion of acetylated polyamines. As polyamine levels fall in treated cells, the concentrations of analogues increase. Since they do not function in cell metabolism as do polyamines, division stops and apoptosis begins (Casero & Woster, 2001; Frydman & Valasinas, 1999; Ha et al., 1998).

In the present study, we worked with pre-emergent spore fractions, which, although relatively homogeneous, were not actively dividing cells. Thus, effects of analogues seen on dividing mammalian cells such as SSAT induction, reduction in ODC and AdoMetdc activities, could not be readily observed. However, these analogues had several definitive effects on polyamine metabolism of *Enc. cuniculi*, including reduction of spermine uptake and interconversion (SL-11144, SL-11158) and mixed inhibition of SSAT (SL-11158). BW-1 was a substrate for PAO and in vivo is thus a likely competitive inhibitor of the enzyme with N1-acetylspermine as substrate. The related analogue MDL 27695 [a bis(benzyl) 3-7-3 analogue; Fig. 1] is debenzylated by mammalian PAO (Bitonti et al., 1990). MDL 27695 at 1 mM had modest (33 %) substrate activity in the *Enc. cuniculi* PAO assay. BW-1, a bis(phenylbenzyl) 3-7-3 analogue, had higher substrate activity (54 %) in this system, and, used in the presence of the natural substrate, stimulated enzyme activity, by 2-6-fold (Table 5).

These studies indicate that *Enc. cuniculi* has significant

### Table 5. Polyamine analogues as substrates or inhibitors of *Enc. cuniculi* PAO

<table>
<thead>
<tr>
<th>Compound</th>
<th>Concentration</th>
<th>Percentage of control activity (substrate)</th>
<th>Percentage inhibition of activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1-Acetylspermine (control)</td>
<td>1 mM</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>bis(Benzyl)putrescine</td>
<td>1 mM</td>
<td>0</td>
<td>ND</td>
</tr>
<tr>
<td>SL-11061</td>
<td>100 µM</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>SL-11093</td>
<td>100 µM</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>SL-11144</td>
<td>100 µM</td>
<td>0</td>
<td>75</td>
</tr>
<tr>
<td>SL-11158</td>
<td>100 µM</td>
<td>0</td>
<td>57</td>
</tr>
<tr>
<td>MDL 27695</td>
<td>1 mM</td>
<td>33-9</td>
<td>ND</td>
</tr>
<tr>
<td>Aminoguanidine</td>
<td>1 µM</td>
<td>56-1</td>
<td>15</td>
</tr>
<tr>
<td>Aminoguanidine</td>
<td>10 µM</td>
<td>38-8</td>
<td>22</td>
</tr>
<tr>
<td>Aminoguanidine</td>
<td>100 µM</td>
<td>33-7</td>
<td>33</td>
</tr>
<tr>
<td>Aminoguanidine</td>
<td>500 µM</td>
<td>0</td>
<td>88</td>
</tr>
<tr>
<td>Benzylamine</td>
<td>100 µM</td>
<td>16-4</td>
<td>ND</td>
</tr>
<tr>
<td>MDL 72527</td>
<td>10 µM</td>
<td>ND</td>
<td>+7-5</td>
</tr>
<tr>
<td>MDL 72527</td>
<td>50 µM</td>
<td>ND</td>
<td>+29</td>
</tr>
<tr>
<td>MDL 72527</td>
<td>100 µM</td>
<td>91-3</td>
<td>+30</td>
</tr>
<tr>
<td>MDL 72521</td>
<td>100 µM</td>
<td>101-3</td>
<td>+55</td>
</tr>
<tr>
<td>MDL 72521</td>
<td>10 µM</td>
<td>103</td>
<td>+49</td>
</tr>
<tr>
<td>MGBG*</td>
<td>100 µM</td>
<td>ND</td>
<td>+360</td>
</tr>
<tr>
<td>BW-1</td>
<td>1 mM</td>
<td>54-9</td>
<td>+260</td>
</tr>
<tr>
<td>Pargyline</td>
<td>50 µM</td>
<td>ND</td>
<td>80</td>
</tr>
</tbody>
</table>

*MGBG, Methylglyoxal-bis(guanylhydrazone).*
polyamine scavenging potential with spermine the preferred substrate and it is likely that interconversion of polyamines readily occurs in this intracellular parasite. SL-11144, SL-11158 and BW-1 interfere with polyamine uptake and interconversion in the intact pre-emergent spores, while SL-11158 gives a mixed type of inhibition of parasite SSAT. BW-1 is a substrate for parasite PAO and NMR studies in progress indicate two products are formed from $[^{13}C]BW-1$, a carboxylic acid and an aldehyde, which is consistent with an oxidation pathway (P. Woster, personal communication). All these effects occur at similar analogue concentrations, indicating that the mechanism of action of these agents in vivo targets this pathway.

Since existing chemotherapeutic agents for the microsporidia are not universally curative in human infections (Wittner & Weiss, 1999), more effective agents are needed. Continuing studies are aimed at developing more active agents by examining structure–activity relationships and clarifying mechanism(s) of action.

ACKNOWLEDGEMENTS

This work has been supported by grants from the National Institutes of Health (#2ROI-041398-06 to M. W. and A44-AI30904-03 to B. F.), and a Pace University Scholarly Research Award (C. J. B.). The authors thank Jenny Gallardo, Amy Kirner and Maryann Soliman for technical help.

REFERENCES


