Inhibition of indoleamine 2,3-dioxygenase activity by levo-1-methyl tryptophan blocks gamma interferon-induced chlamydia trachomatis persistence in human epithelial cells

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Gamma interferon (IFN-γ) induces expression of the tryptophan-catabolizing enzyme indoleamine 2,3-dioxygenase (IDO1) in human epithelial cells, the permissive cells for the obligate intracellular bacterium Chlamydia trachomatis. IDO1 depletes tryptophan by catabolizing it to kynurenine with consequences for C. trachomatis, which is a tryptophan auxotroph. In vitro studies reveal that tryptophan depletion can result in the formation of persistent (viable but noncultivable) chlamydial forms. Here, we tested the effects of the IDO1 inhibitor, levo-1-methyl-tryptophan (L-1MT), on IFN-γ-induced C. trachomatis persistence. We found that addition of 0.2 mM L-1MT to IFN-γ-exposed infected HeLa cell cultures restricted IDO1 activity at the mid-stage (20 h postinfection [hpi]) of the chlamydial developmental cycle. This delayed tryptophan depletion until the late stage (38 hpi) of the cycle. Parallel morphological and gene expression studies indicated a consequence of the delay was a block in the induction of C. trachomatis persistence by IFN-γ. Furthermore, L-1MT addition allowed C. trachomatis to undergo secondary differentiation, albeit with limited productive multiplication of the bacterium. IFN-γ-induced persistent infections in epithelial cells have been previously reported to be more resistant to doxycycline than normal productive infections in vitro. Pertinent to this observation, we found that L-1MT significantly improved the efficacy of doxycycline in clearing persistent C. trachomatis forms. It has been postulated that persistent forms of C. trachomatis may contribute to chronic chlamydial disease. Our findings suggest that IDO1 inhibitors such as L-1MT might provide a novel means to investigate, and potentially target, persistent chlamydial forms, particularly in conjunction with conventional therapeutics.

Chlamydia trachomatis is an obligate intracellular bacterium that has a tropism for the columnar epithelial cells of the conjunctiva (serovars A to C) and the urogenital tract (serovars D to K) (42). Most C. trachomatis infections are asymptomatic and therefore remain undetected (36). While many individuals eventually clear infection, clearance can take several months to several years (25, 26). If left untreated, C. trachomatis infections can progress to chronic inflammatory disease. Chronic ocular infection can result in trachoma, one of the leading causes of preventable blindness (43, 55). C. trachomatis is also the major bacterial sexually transmitted agent worldwide, commonly infecting the male urethra and female endocervix (42). Bacteria can ascend from the endocervix into the endometrium and fallopian tubes; chronic infection at these sites is associated with pelvic inflammatory disease (PID) and salpingitis, potentially resulting in tubal infertility or ectopic pregnancy (reviewed in reference 13). The pathological sequelae observed during chronic C. trachomatis infections have been proposed to result from the induction of a sustained inflammatory response to persistent bacteria (43). “Chlamydial persistence” in vitro has been described as an alternative phase of the chlamydial developmental cycle in which bacteria enter a morphologically distinct viable but noncultivable growth stage that can result in a long-term relationship with their host cells (8). Indirect evidence that C. trachomatis could persist in vivo in this altered growth state arises from studies describing the detection of chlamydial antigen and nucleic acid in tissues in the absence of cultivability (22, 35) and documentation of recurrent chlamydial disease when reinfection was unlikely (18, 54).

The C. trachomatis developmental cycle is biphasic, usually characterized by alternating infectious elementary body (EB)
and noninfectious reticulate body (RB) stages. EBs infect epithelial cells and then differentiate into RBs within a host-derived vacuole termed an “inclusion” (28). After RB multiplication by binary fission, RBs redifferentiate into EBs and egress from infected epithelial cells to infect neighboring cells (reviewed in reference 1). However, this developmental cycle is disrupted under stressful growth conditions in vitro, such as those imposed by gamma interferon (IFN-γ) (1, 10), antibiotics (17, 23), nutrient deprivation, herpes simplex virus (HSV) coinfection (57), and extracellular adenosine (37). Under these conditions, bacteria survive by entering into a persistent mode of growth that is typified by the formation of large, morphologically aberrant RBs (ARBs) in which bacterial chromosomes continue to divide, but binary fission and differentiation to EB are inhibited. Removal of the stress generally results in reversal of these changes and differentiation into infectious EBs (9).

The in vitro model of IFN-γ-induced persistence and reactivation of C. trachomatis has been particularly well studied (5, 6, 10). In human epithelial cells, IFN-γ induces the expression of the enzyme indoleamine-2,3 dioxygenase (IDO1), which catabolizes tryptophan to kynurenine (20, 53). Such depletion interferes with the growth of C. trachomatis, which is a tryptophan auxotroph (14, 16). Continuous exposure to IFN-γ at inhibitory concentrations results in the eradication of the infection. However, exposure to subinhibitory IFN-γ concentrations, which may be a likely scenario in vivo, results in the development of persistent forms (6). The ability to develop into a persistent form may be a key mechanism by which C. trachomatis survives and establishes long-term infections in the human host (21). Persistent forms may also be associated with the pathology observed during chronic C. trachomatis infection (6–8) and may underlie recurrent disease in the absence of documented reinfection (18, 54). Hence, strategies to block development of persistent forms and/or to eradicate established persistent forms could likely benefit the host.

The IDO inhibitor 1-methyl-DL-tryptophan (1-MT) has previously been demonstrated to inhibit IDO-mediated tryptophan catabolism in C. pneumoniae-infected cells (33, 34). Levo-methyl-tryptophan (L-1MT) is a specific IDO1 inhibitor that can accumulate to steady-state levels in vivo that are sufficient to inhibit this enzyme (51). Nontoxic IDO inhibitors, similar to L-1MT, have already entered clinical trials as potential immunotherapeutic agents for the treatment of cancer (http://clinicaltrials.gov/ct2/show/NCT00739609), because they trigger antigen immaturity, partially by improving T-cell function (38), and act synergistically with conventional chemotherapy (29). In this in vitro study, we investigated the effects of L-1MT on C. trachomatis persistence. The results reported here indicate that L-1MT blocks IFN-γ-induced persistence of C. trachomatis and reactivates C. trachomatis from established persistent growth. Significantly, L-1MT limited the production of infectious bacteria under each of the experimental conditions and improved the efficacy of doxycycline in eradicating persistent bacterial forms. In addition to providing a novel mechanism to target IFN-γ-induced doxycycline-resistant persistent forms, L-1MT can be useful to further our understanding of the IFN-γ–tryptophan–IDO1 axis, the ability of C. trachomatis to persist, and its consequences to the host.

MATERIALS AND METHODS

C. trachomatis infections and cell culture conditions. HeLa 229 cells (hereafter, “HeLa cells”) were obtained from the ATCC and routinely propagated using antibiotic-free complete RPMI 1640 (Corning) culture medium, consisting of RPMI 1640 (Invitrogen) supplemented with 200 mM glutamine (Invitrogen), 0.25% (wt/vol) glucose (Sigma), and 10% fetal calf serum (Invitrogen). Human AB serum (Sigma) was used in place of fetal calf serum (FCS) in performing the described experiments (RP-10). Cells were seeded in 6- or 12-well culture plates in RP-10 and cultivated for 24 to 36 h before infection. C. trachomatis serovar D (D/UW-3/Cx) was used to infect HeLa cells at a multiplicity of infection (MOI) of 2 in all experiments (15). Infections were performed by adding 1 ml/well of C. trachomatis serovar D diluted in SPG (10 mM sodium phosphate [pH 7.2], 0.25 M glucose, 5 mM L-glutamic acid) to 6-well culture plates, which were centrifuged at 400 × g for 40 min at 37°C. Immediately after infection, SPG was removed and replaced with RP-10 alone, 10 ng/ml (200 U/ml) IFN-γ (Peprotech), L-1MT (Sigma), or L-1MT plus 10 ng/ml IFN-γ. In some cases, 40 μg/ml tryptophan was added to cultures with L-1MT in the presence or absence of IFN-γ. IFN-γ (Peprotech) was used at 0.05 to 1.0 μg/ml and was within the range of concentrations used in the clinic (http://clinicaltrials.gov/ct2/show/NCT00739609), because they showed clinical benefit (36). Significant anti-inflammatory effects of IFN-γ were observed at concentrations of 0.5 to 1 μg/ml IFN-γ (36). L-1MT was added at concentrations of 0.05 to 1.0 μM. IFN-γ treatment was also used to examine the consequences of IDO inhibition in vivo.

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and kynurenine, respectively. The peaks of tryptophan or kynurenine were identified using a linear gradient consisting of methanol (100%) and acetonitrile (80%). For kynurenine determination, the column was eluted with a methanol (100%), acetonitrile (80%) equilibrated at a flow rate of 0.5 ml/min with 0.1 M sodium acetate buffer (pH 4.8). For tryptophan measurement, subtractive masking was also used to enumerate the number of EBs per cross-sectional inclusion area. For consistency, the same threshold value (100) was used for all micrographs, and EBs were sized as between 0.02 and 0.18 μm², with a circularity of 0.45 to 1.0. Heterogeneity in EB size arises because not every EB within the cross-sectional area is within the same plane. These values were chosen after tests using subtractive masking with several images to ensure that no RBs were selected using these parameters. Subtractive masking was also used to enumerate the number of RBs per inclusion. Abrerrant inclusions were independently counted by two individuals.

**Dosycycline and L-1MT treatment and assessment of recoverable IFU.** HeLa cells were seeded in 12-well plates 24 h before infection. Cells were then infected with serovar D and cultivated in RP-10 to 10 ng/ml IFN-γ for 38 h to induce persistence. In the initial experiments, persistent cultures were exposed to doxycycline concentrations ranging from 0.05 to 50 μg/ml. In these experiments, it was observed that exposure to doxycycline concentrations above 20 μg/ml for 48 h was toxic to HeLa cells, consistent with previous observations with other mammalian cell lines (19, 41). Doxycycline, at a concentration of 1 μg/ml, was used alone or in combination with 0.2 mM L-1MT in the experiments reported here. To assess the recoverable IFU, treated cells were reactivated by replacing the medium with RP-10 with 40 μg/ml tryptophan and 1 μg/ml cycloheximide for 48 h. Culture media in C. trachomatis-infected HeLa cell cultures were replaced with SPG, and the cells were scrapped from the culture plates. The cell scrapings were frozen at –80°C until ready to use, and the number of recoverable IFU was determined as described earlier.

**Statistical analyses.** Statistical analyses were based on data from three to five experiments. Student’s t test (50) was utilized to determine differences between control and experimental conditions.

**RESULTS**

**IFN-γ induces IDO1 expression in HeLa 229 cells.** Exposure of HeLa cells to IFN-γ is well documented to induce IDO1 expression (53). Therefore, HeLa cells were exposed to 10 ng/ml IFN-γ and the level of IDO1 induction in C. trachomatis serovar D infection was assessed. Under these conditions, infection rates of 40 to 50% were detected at 38 hpi; pertinently, cycloheximide, an inhibitor of translation routinely used to prevent the proliferation of mammalian cells, was not added to the HeLa cultures in these experiments to prevent inhibition of IDO1 expression (5). IDO1 mRNA expression was first determined in C. trachomatis-infected HeLa cells and matched mock-infected control cultures cultivated under different con-
IDO1-mediated tryptophan catabolism is inhibited at 20 h postinfection by the addition of L-1MT. IDO catalyzes tryptophan via the kynurenine pathway (46, 53). Therefore, tryptophan and kynurenine levels in cell culture supernatants can be used to determine the induction of IDO activity by IFN-γ. We examined tryptophan and kynurenine levels in mock-infected and \textit{C. trachomatis}-infected HeLa cells under the following conditions: (i) in medium alone, (ii) with addition of 0.2 mM L-1MT, (iii) with addition of 10 ng/ml IFN-γ, or (iv) with addition of both 10 ng/ml IFN-γ and 0.2 mM L-1MT. Because one developmental cycle of \textit{C. trachomatis} serovar D is typically completed in 48 h, tryptophan catabolism was measured in culture supernatants at early (8 hpi), middle (20 hpi), and mid-late (38 hpi) stages of chlamydial development. No significant difference in tryptophan levels was observed between the different culture conditions at 8 hpi (data not shown). At 20 hpi, tryptophan fell below the level of detection (0.2 μM) in cell cultures exposed to IFN-γ alone, but not in 0.2 mM L-1MT-supplemented IFN-γ-exposed cultures (Fig. 2A). These results indicate that L-1MT inhibited IFN-γ-induced IDO1 activity at the mid-stage (20 hpi) of \textit{C. trachomatis} development. At 38 hpi, tryptophan levels in all culture supernatants from IFN-γ-exposed HeLa cells were below the 0.2 μM detection limit, in contrast to \textit{C. trachomatis}-infected cells treated with IFN-γ plus L-1MT, which retained 0.26 μM tryptophan. This suggests that >99% of tryptophan in the culture media was either utilized or catabolized in all cultures exposed to IFN-γ at this later stage of \textit{C. trachomatis} development (Fig. 2B). Furthermore, at 20 and 38 hpi, kynurenine was produced in all HeLa cell cultures that were exposed to 10 ng/ml IFN-γ (Fig. 2C and D). Because it was confirmed that kynurenine was absent in unused culture media under the four conditions evaluated, its presence in culture supernatants indicates that IFN-γ-induced IDO1 activity resulted in kynurenine production, as reported previously (32, 52, 58). We also noted that significant differences in kynurenine production could only be observed after a shorter period (20 hpi) of IFN-γ exposure, at which time kynurenine is unlikely to have been catabolized into downstream metabolites.

L-1MT has no toxic effects on HeLa 229 cells and does not inhibit \textit{C. trachomatis} growth. To assess the toxicity of L-1MT on host cells, HeLa cell cultures were exposed to 0.2 mM or 1 mM L-1MT for 48 h and assessed for apoptosis or necrosis by double staining using annexin V and propidium iodide (PI). Flow cytometric analyses demonstrated that exposure of HeLa cells to 0.2 mM and 1 mM L-1MT (i.e., five times more than the dosage used in this study) allowed the recovery of ~95% viable cells, which is comparable to the untreated negative control (Fig. 3). In contrast, HeLa cells exposed to 1 mM H$_2$O$_2$ displayed both apoptosis and necrosis (Fig. 3).

We also demonstrated that L-1MT alone does not alter the normal development of \textit{C. trachomatis}, as shown by the similar ultrastructural morphology of the inclusions formed in the presence of 0.2 mM L-1MT and the untreated control (Fig. 4A). In addition, neither 0.2 mM nor 1 mM L-1MT decreased recoverable IFU from \textit{C. trachomatis}-infected cells at 48 hpi (Fig. 4B).

L-1MT blocks IFN-γ-induced \textit{C. trachomatis} persistence. IFN-γ can induce \textit{C. trachomatis} to enter into a persistent mode of growth (40). Inclusions formed during IFN-γ-medi-
ated persistence are small and contain aberrant RBs (ARBs) that display a distinct gene expression profile. IFN-γ-induced IDO expression has been demonstrated to restrict C. trachomatis growth, which is attributed to tryptophan depletion because it is reversed by addition of tryptophan. In the experiments described below, the temporal inhibition of IDO1 activity by 0.2 mM L-1MT was observed to block IFN-γ-induced C. trachomatis persistence. We assessed the capacity of 0.2 mM L-1MT to inhibit the effects of IFN-γ using quantitative analyses of inclusion images obtained by electron microscopy and through gene expression studies.

To determine the effect of L-1MT on C. trachomatis growth at the ultrastructural level, a morphological assessment of C. trachomatis inclusions formed under different growth conditions was performed at 48 hpi and quantitatively evaluated using ImageJ software (Table 2). The mean inclusion cross-sectional area of control cultures was 120.9 μm², with a mean of 146 EBs per inclusion (Fig. 5A to C). This is characteristic...
of normal development. Treatment with IFN-γ (Fig. 5D to F) significantly decreased the average cross-sectional area of inclusions to 18.8 μm² (P < 0.0001), with a mean of less than one EB, and eight aberrant RBs per inclusion. Relative to treatment with IFN-γ alone, exposure to both IFN-γ and L-1MT (Fig. 4G to I) significantly increased the average inclusion area to 46.7 μm², decreased the mean number of aberrant forms to less than one per inclusion (P < 0.0001), and increased average EB numbers to 13/inclusion (P < 0.0001). To evaluate the possibility that there were condition-specific differences in the number of EBs and RBs per inclusion, alterations in inclusion size and the numbers of EBs, RBs, and aberrant forms per cross-sectional area were also calculated (Table 3). The results of these analyses corroborate the pattern of findings presented in Table 2 and eliminate the possibility that decreased numbers of EBs and RBs resulted from a proportional decrease in the size of the inclusion. Thus, ultrastructural analyses indicate that addition of L-1MT to C. trachomatis-infected cells induced the formation of inclusions with unique morphological characteristics that are distinct from persistent inclusions.

To further confirm at the molecular level whether L-1MT treatment blocks the induction of persistence, we performed gene expression analyses of two early chlamydial genes (euo and groEL) and two late chlamydial genes (omcB and hctA). A comparison of the gene expression pattern of C. trachomatis grown in L-1MT-treated culture with that of persistent forms relative to the normal growth control is shown in Fig. 6. Consistent with previous data (6, 10), euo expression and groEL expression were upregulated during IFN-γ-induced persistence compared to normal infection (Fig. 6). euo and groEL genes are typically expressed early during chlamydial development. Because we did not observe an upregulation of euo or groEL in the culture treated with L-1MT, this indicates that these genes are differentially regulated in IFN-γ-induced persistence and IFN-γ-L-1MT exposure. This finding is supported by the observation that in contrast to persistent C. trachomatis cultures, infected cultures grown under conditions that included L-1MT upregulated the late genes omcB and hctA. These genes encode structural and regulatory proteins required for the transition of RBs back into EBs (10, 45). These data demonstrate that unlike persistent growth, C. trachomatis development under conditions with L-1MT allows for normal RB transformation to EBs. Based on the expression of selected early and late genes, C. trachomatis growth pattern exhibited in the presence of both IFN-γ and L-1MT is distinct from C. trachomatis persistence, displayed in the presence of IFN-γ alone. Together, these data indicate that the L-1MT treatment could block the induction of C. trachomatis persistence by IFN-γ. Intriguingly, exposure to L-1MT resulted in a unique development pattern, as indicated both by ultrastructural studies and by gene expression analyses.

L-1MT treatment results in the limited replication of C. trachomatis. Preliminary studies indicated that L-1MT addition to IFN-γ-treated cells did not reduce the number of C. trachomatis inclusions formed at 38 hpi (data not shown). This is consistent with a study by Pantoja et al. with the C. pneumoniae infection model using 1MT, which is a mix of both L-1MT and dextro-1-methyl tryptophan (D-1MT). The distinct growth pattern of bacteria formed in IFN-γ-L-1MT-exposed cultures prompted us to further evaluate the effect of adding L-1MT to IFN-γ-exposed cells on chlamydial development. This was achieved by assessing IFUs that could be recovered from cell lysates and cell culture supernatants at 38, 48, and 72 hpi (Fig. 7).

Characteristic of normal development, the IFU in cell lysates and culture supernatants from control cultures and cultures exposed to L-1MT alone increased over the course of 72

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**TABLE 2.** Partial reversion by L-1MT of the effect of IFN-γ on inclusion size and contents as shown by ultrastructural analyses.

<table>
<thead>
<tr>
<th>Expt</th>
<th>Area (μm²) ± d</th>
<th>No. of EBs/ inclusion</th>
<th>No. of RBs/ inclusion</th>
<th>No. of ARBs/ inclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>120.9 ± 40²</td>
<td>146 ± 82²</td>
<td>33.2 ± 18.2²</td>
<td>0.1 ± 0.3²</td>
</tr>
<tr>
<td>+IFN-γ</td>
<td>18.8 ± 8.6²</td>
<td>0.5 ± 0.8²</td>
<td>0.5 ± 0.8²</td>
<td>7.6 ± 3.1²</td>
</tr>
<tr>
<td>+IFN-γ +L-1MT</td>
<td>46.7 ± 27.9²</td>
<td>13.4 ± 8.3²</td>
<td>8.6 ± 6.3²</td>
<td>0.9 ± 1.4²</td>
</tr>
</tbody>
</table>

² Values represent the mean ± standard deviation inclusion cross-sectional area in 10 randomly selected electron micrographs (EMs).

Values represent the mean ± standard deviation numbers of elementary bodies (EBs), reticulate bodies (RBs), and aberrant reticulate bodies (ARBs) observed in 10 randomly selected EMs. EBs were counted using ImageJ as described in Materials and Methods. The distinction between RBs and ARBs was scored independently by two individuals.

Values observed in the presence of IFN-γ and L-1MT were significantly different from those observed in the presence of IFN-γ alone (Student’s t test, P < 0.0001).
Consistent with the persistent growth of bacteria, cell lysates and culture supernatants from *C. trachomatis*-infected HeLa cultures exposed to IFN-γ alone did not yield detectable IFU up to 48 hpi and yielded significantly lower IFU at 72 hpi compared to all other culture conditions. In IFN-γ-L-1MT-exposed *C. trachomatis*-infected HeLa cell cultures, we observed limited IFU from cell lysates and cell culture supernatants collected at 48 hpi, and this further decreased significantly at 72 hpi (Fig. 7A). Furthermore, in contrast to the control, immunofluorescent staining for chlamydia in IFN-γ-L-1MT-exposed cultures revealed little evidence of secondary infections at 72 hpi (Fig. 7B). We also did not observe evidence of persistent forms of *C. trachomatis* in IFN-γ-L-1MT-exposed cultures (Fig. 7B).

Together these data indicate that addition of L-1MT to IFN-γ-treated cultures blocked the induction of persistence; interestingly, this occurs via a mechanism that severely restricts recoverable IFU.

Further support that L-1MT limits the productive multiplication of *C. trachomatis* exposed to IFN-γ was obtained from data demonstrating that the ratio of chlamydia to host DNA was not significantly increased by the addition of L-1MT (Fig. 8). In contrast, addition of tryptophan to IFN-γ-L-1MT-exposed cells resulted in more than a log-fold increase in the relative chlamydial genome copy number (Fig. 8). These data suggest that unlike tryptophan, which has been demonstrated

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**TABLE 3.** The reduced number of EBs/μm² of inclusion area induced by IFN-γ exposure is not reversed by L-1MT

<table>
<thead>
<tr>
<th>Expt</th>
<th>No. of EBs/μm²</th>
<th>RBs/μm²</th>
<th>ARBs/μm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>1.18 ± 0.45</td>
<td>0.29 ± 0.14</td>
<td>0.001 ± 0.002</td>
</tr>
<tr>
<td>+IFN-γ</td>
<td>0.03 ± 0.06</td>
<td>0.02 ± 0.03</td>
<td>0.412 ± 0.412</td>
</tr>
<tr>
<td>+IFN-γ, +L-1MT</td>
<td>0.33 ± 0.17</td>
<td>0.21 ± 0.16</td>
<td>0.034 ± 0.059</td>
</tr>
</tbody>
</table>

*a The values shown represent means ± standard deviations from the same 10 samples analyzed in Table 1.

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**FIG. 5.** Treatment with L-1MT results in a unique morphological characteristic of *C. trachomatis* inclusions. Electron micrographs of 3 representative inclusions from *C. trachomatis* grown in medium alone (control) (A to C), medium with 10 ng/ml IFN-γ (D to F), and medium with 10 ng/ml IFN-γ together with 0.2 mM L-1MT (G to I). The scale bars represent 0.5 μm. The cells were harvested at 48 hpi and processed for transmission electron microscopy. Inclusions that were formed in culture with 10 ng/ml IFN-γ plus 0.2 mM L-1MT formed significantly less EBs and RBs than those that were grown in medium alone.

**FIG. 6.** *C. trachomatis* cultures that were exposed to IFN-γ exhibited a unique gene expression pattern with the addition of 0.2 mM L-1MT. Data are expressed as fold change compared to the no-IFN-γ control (medium alone), which was designated a value of 1 (horizontal line). White bars represent gene expression of persistent (+IFN-γ) and IFN-γ- and L-1MT-treated *C. trachomatis* were evaluated using Student’s t test. Comparisons of gene expressions between the two conditions reveal significant differences in the expression level of the indicated gene. *, P < 0.05; **, P < 0.01.
to induce the reactivation of *C. trachomatis* from persistent forms to normal productive development, L-1MT does not support the productive multiplication of the bacterium.

**Effects of exogenous tryptophan on IFN-γ–L-1MT-exposed C. trachomatis-infected HeLa cells.** To further investigate the effects of the addition of exogenous tryptophan on *C. trachomatis*-infected L-1MT-treated HeLa cells, qPCR was used to quantify *trpB* gene expression in cultures with L-1MT or L-1MT supplemented with tryptophan, in the absence or presence of IFN-γ. Our results indicate that the addition of L-1MT to IFN-γ-exposed cells decreased *trpB* gene expression compared to IFN-γ alone (Fig. 9). However, infected cultures treated with IFN-γ and L-1MT maintained elevated *trpB* expression compared to untreated (no-IFN-γ) control cultures, indicating that L-1MT by itself does not inhibit *trpB* expression. We interpret this finding to indicate that even during L-1MT exposure, *C. trachomatis* continues to respond to tryptophan depletion in the host cell (3, 59). Consistent with this interpretation, a striking decrease in *trpB* expression was observed when tryptophan was added to cultures treated with IFN-γ and L-1MT. Therefore, exogenous tryptophan can repress the *trpB* gene expression in the presence of L-1MT (Fig. 9), indicating that L-1MT likely does not interfere with tryptophan transport into the chlamydial inclusion.

Next, we examined whether the addition of tryptophan raised the recoverable IFU in IFN-γ-exposed cells in the presence of L-1MT. Here we found that the addition of tryptophan not only rescued the persistent growth phenotype, but it could also countermand the decrease in recoverable IFU that results from exposure to L-1MT (Fig. 10). These data in conjunction with our other findings reveal that L-1MT’s effect on chlamydial growth primarily arises from its ability to modulate tryptophan levels in cells infected by *C. trachomatis* and consequently to the bacterium.
L-1MT treatment can reactivate *C. trachomatis* from an established persistent growth mode. *C. trachomatis* that have entered into an IFN-γ-induced persistent mode of growth can be reactivated by removing IFN-γ and adding exogenous tryptophan. Therefore, the ability of L-1MT to reactivate an established persistent *C. trachomatis* infection was examined. For these investigations, 0.2 mM L-1MT was added to IFN-γ-treated cultures at 38 hpi, after persistent forms had developed. Ultrastructural analyses clearly indicated that L-1MT could reactivate *C. trachomatis* from a persistent mode of growth. A change in the morphology of persistent chlamydial forms was observed as early as 24 h post-L-1MT treatment, and reactivation into EBs was observed at 48 h post-L-1MT treatment. However, in contrast to cultures exposed to IFN-γ alone, the number of inclusions in persistent *C. trachomatis* cultures reactivated with L-1MT decreased significantly over time. Quantitation revealed significantly fewer inclusions at 48 h post-L-1MT treatment compared to 24 h post-L-1MT treatment (*P* < 0.01). These data indicate that unlike the outcome of conventional reactivation of persistent *C. trachomatis* by IFN-γ removal and/or tryptophan replenishment, reactivation by adding L-1MT severely restricts bacterial multiplication.

**Treatment with L-1MT sensitizes persistent C. trachomatis to doxycycline.** In a recent study by Reveneau and coworkers, IFN-γ-induced persistent forms of *C. trachomatis* were more refractory to doxycycline exposure than those that underwent normal development (39). As doxycycline is one of the two antibiotics used most often to treat *C. trachomatis* infection, we examined the effect of L-1MT on doxycycline resistance of persistent forms of *C. trachomatis*. Because L-1MT can reactivate *C. trachomatis* from persistent growth to a limited extent, we tested whether combining L-1MT with doxycycline was more effective at eradicating IFN-γ-induced persistent forms of *C. trachomatis* than doxycycline alone.

The experimental protocol depicted in Fig. 12A was used to determine the number of recoverable IFU when IFN-γ-treated cultures were also exposed to L-1MT, doxycycline, or doxycycline plus L-1MT. Briefly, IFN-γ was added at the time of infection to induce persistence. At 38 hpi, persistent cultures were treated with doxycycline, L-1MT, or both for an additional 24 h. Following this, IFN-γ, doxycycline, and L-1MT were substituted for by culture medium supplemented with tryptophan and cycloheximide in 48 h, after which recoverable IFU were measured.

Recoverable IFU were decreased by approximately 4-fold by exposure to 0.2 mM L-1MT alone and 9-fold by exposure to 1 μg/ml doxycycline alone, compared to untreated cultures (Fig. 12B). Strikingly, treatment with 0.2 mM L-1MT combined with 1 μg/ml doxycycline reduced recoverable IFU to a level below the assay’s detection limit. Indeed, this combination was more effective at reducing recoverable IFU than using doxycycline alone, even at concentrations as high as 10 μg/ml (data not shown). Therefore, these data indicate that the combination L-1MT and doxycycline is more effective at clearing persistent forms of *C. trachomatis* than doxycycline alone.

**DISCUSSION**

Problems associated with persistent chlamydial growth include the possibilities that it (i) permits immune evasion (6), (ii) provides a reservoir of bacteria that can be reactivated when conditions in the infected microenvironment are permissive (9, 10), and (iii) may underlie the recalcitrance of chlamydiae to some commonly used antibiotics (11, 12, 39, 60). In this study, we explored the effects of the specific IDO1 inhib-
itor L-1MT on the growth and development of *C. trachomatis* in HeLa cells. Our results indicate that 0.2 mM L-1MT can (i) block IFN-γ/H9253-mediated *C. trachomatis* persistence, (ii) limit the formation of infectious EBs, and (iii) increase the susceptibility of persistent *C. trachomatis* forms to doxycycline treatment.

We hypothesize that the mechanism underlying the ability of L-1MT to rescue *C. trachomatis* from IFN-γ-mediated persistence, while limiting the productive multiplication of the bacterium, involves the temporal depletion of tryptophan (Table 4). We infer that because L-1MT prevented tryptophan depletion at the mid-stage of chlamydial development (20 hpi), *C. trachomatis* bypassed IFN-γ-induced persistence. However, by permitting depletion of tryptophan at the mid-late stage of the chlamydial development (38 hpi), the available tryptophan was insufficient to support normal late-stage development of bacteria. Thus, as a consequence of the addition of L-1MT to IFN-γ-exposed *C. trachomatis*, a unique chlamydial growth pattern was observed that is distinct from persistent forms and also characterized by a limited productive release of infectious EBs (Fig. 13). Although L-1MT is considered a stable molecule (56, 61), its half-life under the conditions we have used is unknown. Therefore, it is also possible that the reduced depletion of tryptophan at 38 hpi resulted from a decreased inhibition of IDO1 at that time.

Reveneau and coworkers reported that doxycycline, a first-line antibiotic commonly used to treat *C. trachomatis* infections, was more effective in clearing normal replicating *C. trachomatis* infections *in vitro* than those that were cultivated in the presence of IFN-γ. Their observations permitted them to conclude that IFN-γ-induced persistent forms of *C. trachomatis* were more resistant to this antibiotic (39). Although L-1MT blocked persistence, it also severely restricted bacterial multiplication. Therefore, we investigated whether using L-1MT in combination with doxycycline was more effective against persistent bacteria than doxycycline alone. Our data indicate that L-1MT reactivated persistent *C. trachomatis* ineffectually, resulting in a sharp decrease in the number of EBs observed ultrastructurally and IFUs measured biologically. This ineffectual reactivation resulted in an increased susceptibility to doxycycline. Although as yet unexplored, we propose that the increased sensitivity to doxycycline in the presence of L-1MT results from the molecular mechanism by which doxycycline functions—that is blockade of protein synthesis by binding the ribosome acceptor site and therefore inhibiting the association of aminoacyl-tRNA with the mRNA-ribosome complex. It is known that tryptophan deprivation severely decreases protein synthesis in persistent *C. trachomatis* forms without completely blocking genome replication (31). Therefore, even a limited alleviation of tryptophan deprivation likely provides molecular targets for doxycycline by restoring protein synthesis to some measure. Our finding that a combination of L-1MT and doxycycline is superior to the use of doxycycline alone is similar to previous suggestions that combination drug treatment of *C. trachomatis* can be superior to therapy with a single antibiotic (49).

Currently, there is no direct and indisputable evidence that
IFN-γ-mediated persistent forms of chlamydiae exist (12), clinical (18, 35), and physiological (4) studies support measured. (B) Recoverable IFU from persistent substituted for by culture medium supplemented with tryptophan (Trp), doxycycline, and L-1MT were sub-
hutional 24 h. Following this, IFN-γ, doxycycline, L-1MT, or doxycycline with L-1MT for an addi-
to induce persistence. At 38 hpi, persistent cultures were treated with
C. trachomatis
in vivo
infections to human
C. trachomatis
in nonhuman primate models, it would indicate that partial rescue of auxotropy in combination with therapy that targets replication is a potent mechanism to clear infection by a pathogen. Indeed, we note that auxotrophy is not unusual among intracellular pathogens, where evolution has often driven the loss of a pathogen’s capacity to synthesize metabolites readily available from the host. For example, the intracel-
Table 4. Temporal depletion of tryptophan by addition of L-1MT to IFN-γ-exposed C. trachomatis-infected HeLa cell cultures

<table>
<thead>
<tr>
<th>Time, hpi (stage)</th>
<th>Tryptophan concn (μM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>−IFN-γ&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>8 (early)</td>
<td>26 ± 1.4</td>
</tr>
<tr>
<td>20 (mid)</td>
<td>10 ± 1.9</td>
</tr>
<tr>
<td>38 (mid-late)</td>
<td>3 ± 1.9</td>
</tr>
</tbody>
</table>

<sup>a</sup> Represented by the red path in Fig. 13 (normal development).
<sup>b</sup> Represented by the blue path in Fig. 13 (induction of persistence).
<sup>c</sup> Represented by the green path in Fig. 13 (combined IFN-γ-L-1MT exposure).

We believe that our findings provide sufficient proof of principle to warrant further investigation of the efficacy of L-1MT in human in vitro models and nonhuman primate models of C. trachomatis infection. If the biological half-life of L-1MT at mucosal sites is found to reduce its availability in C. trachoma-
trachomatis
Leishmania is a tryptophan auxotroph (24), which frequently escapes therapeutic surveillance com-
ry occur in vivo when infecting microorganisms like Trichomonas vaginalis could provide an indole source that might be utilized by genital serovars of C. trachomatis to synthesize tryptophan. This phenomenon has been postulated to be detrimental in controlling chronic C. trachomatis infections as it may reactiv-
We hypothesize that this combination approach might be more efficacious for treatment as it would decrease the probability of escape of persistent forms from the effects of doxycycline alone. For these reasons, we propose L-1MT would be a novel and effective approach to experimentally explore, and interfere with, the survival and the long-term association of C. tracho-

FIG. 12. L-1MT improves the efficacy of doxycycline in clearing persistent C. trachomatis infection in HeLa cells. (A) Schematic dia-

persistence occurs in vivo due to the challenging nature of these studies. However, multiple indications from morpholog-
ical (12), clinical (18, 35), and physiological (4) studies support the in vivo occurrence of a C. trachomatis persistent state. If IFN-γ-mediated persistent forms of chlamydiae exist in vivo, a potential therapeutic complication would be the apparent relative resistance of this growth form to doxycycline treatment (39). There are reports of recurrent infections in women who have been previously treated with doxycycline (11, 18). While the majority of recurrent infections likely result from reinfection, it remains possible that some arise from reactivation of small reservoirs of persistent bacteria that have not been fully eliminated by antibiotics. This possibility is supported by the study of Dean et al., who observed multiple, same-serovar recurrent C. trachomatis infections in women over a 2- to 5-year period despite antibiotic treatment (18). Since the most serious ramifications of C. trachomatis infections to human health are primarily associated with chronic or repeated infec-
tions, the observation by Reveneau and coworkers that IFN-γ-induced persistent forms of C. trachomatis are relatively re-
sistant to doxycycline may have serious repercussions. The implication of IFN-γ-mediated persistence in vivo has been elegantly discussed by others (7, 27), and consequently, the use of tryptophan supplementation in combination with antibiotics as a therapeutic approach has previously been proposed (48). The data presented here imply this approach would not be effective in clearing C. trachomatis infection in vivo; indeed, it may be detrimental to disease outcome because reactivation of persistent bacterial forms through tryptophan supplementation would restore efficient production of element-

TABLE 4. Temporal depletion of tryptophan by addition of L-1MT to IFN-γ-exposed C. trachomatis-infected HeLa cell cultures

![Diagram](https://via.placeholder.com/150)

![Graph](https://via.placeholder.com/150)
FIG. 13. Schematic model of the proposed mechanism underlying L-1MT’s ability to block IFN-γ-mediated persistence while limiting the productive multiplication of the bacterium. The red path denotes normal development, blue denotes induction of persistence, and green denotes development in the presence of IFN-γ and 0.2 mM L-1MT. L-1MT prevented tryptophan depletion at the mid-stage of chlamydial development (20 hpi), allowing C. trachomatis to bypass the IFN-γ-induced persistence. However, it allows tryptophan depletion at the mid-late stage of the chlamydial development (38 hpi); hence, the available tryptophan was insufficient to support normal late-stage development of bacteria (Table 4).

Thus, addition of L-1MT to IFN-γ-exposed C. trachomatis results in a temporal tryptophan depletion supporting the unique chlamydial growth pattern that is distinct from persistent forms and also characterized by a limited productive release of infectious EBs.

monly imposed by antileishmanial therapy that targets replication (30). Our studies support the concept that partial restriction of tryptophan availability may also increase the efficacy of such drugs against Leishmania. Thus, our findings may provide insights into the design of new therapeutic approaches that are also more broadly applicable to many intracellular microorganisms.

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