Archives of Razi Institute Journal
"Arch. Razi Inst."

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Research Paper

# The Therapeutic Effects of Atovaquone and Clindamycin on the Reduction of Tissue Cysts of the *PRU* Strain of *Toxoplasma gondii*

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**How to cite this article** Dalimi A, Zouei N, Pirestani M. The Therapeutic Effects of Atovaquone and Clindamycin on the Reduction of Tissue Cysts of the *PRU* Strain of *Toxoplasma gondii*. Archives of Razi Institute Journal. 2026; 81(3):591-598. https://doi.org/10.32598/ARI.81.3.3352

https://doi.org/10.32598/ARI.81.3.3352

**Article info:**
**Received:** 25 Jan 2026
**Accepted:** 12 Feb 2026
**Published:** 01 May 2026

**Keywords:**
Atovaquone (AT), Cerebral toxoplasmosis, Clindamycin (CL), *PRU* strain, *Toxoplasma gondii*

## ABSTRACT

**Introduction:** Despite recent advances in the treatment of cerebral toxoplasmosis, monitoring parasite load and treatment response is still challenging. In the present study, the effect of atovaquone (AT) and clindamycin (CL), alone and in combination, on chronic cerebral toxoplasmosis caused by the *PRU* strain of *Toxoplasma gondii* was investigated in BALB/c mice.

**Materials & Methods:** BALB/c mice aged 6 to 8 weeks were infected by intraperitoneal inoculation of brain cysts of the *PRU* strain of *T. gondii*. Then, the mice were divided into five groups as follows: Group 1 included mice treated with 100 mg/kg of AT, group 2 included mice treated with 400 mg/kg per day of CL, group 3 included mice treated with the combination (AT+CL), group 4 included untreated, infected mice as a positive control (PC), and group 5 included untreated, uninfected mice as a negative control (NC). After the completion of the treatment period, the effect of the drugs in reducing or eliminating parasites in the brain was evaluated by counting the number of brain cysts.

**Results:** The results showed that although AT and CL did not completely remove the cysts from the brain tissue of mice, they significantly reduced the number of tissue cysts in the brain tissue of the treated mice compared to the untreated control group (PC) ($P<0.0001$). AT had a greater anti-toxoplasmic effect than CL, and the difference between the two drugs was highly significant.

**Conclusion:** In conclusion, considering the risks of infection with different strains of *T. gondii*, it is necessary to emphasize the importance of developing effective therapeutic interventions for toxoplasmosis.

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## 1. Introduction

Toxoplasmosis is a globally widespread infection, with particularly high rates in some areas. The demand for new treatments or drugs for toxoplasmosis arises from several key reasons. Current therapies, mainly pyrimethamine and sulfadiazine, often cause severe side effects and require close monitoring of blood levels to prevent toxicity, particularly during prolonged use [1]. Another growing issue is the potential for *Toxoplasma gondii* to develop drug resistance, which may reduce the efficacy of existing medications. Immunocompromised individuals—such as those with HIV/AIDS, undergoing cancer therapy, or receiving organ transplants—face a greater risk of severe toxoplasmosis, and available treatments may not adequately control infections in these patients. Additionally, congenital toxoplasmosis (transmitted during pregnancy) can result in fetal complications like neurological impairment, vision loss, and developmental delays. Better therapeutic approaches could significantly improve outcomes for both mothers and infants [1].

Atovaquone (AT) is an antiprotozoal drug designed to prevent and treat specific protozoal infections. It functions as a structural analog of coenzyme Q (ubiquinone), a critical element in mitochondrial electron transport. By binding to cytochrome b, AT disrupts the mitochondrial membrane potential and interferes with pyrimidine synthesis in the parasite [2, 3], ultimately impairing energy production and causing cell death.

As a standalone treatment, AT is effective against *T. gondii* and *Pneumocystis jirovecii* infections, as well as for malaria prevention [2, 3]. In vitro studies demonstrate its potent activity against tachyzoites at nanogram-per-milliliter concentrations [4, 5], though higher doses are needed to eliminate bradyzoites within cysts [4]. In mouse models of toxoplasmosis, AT showed efficacy alone [6], but its effectiveness improved when combined with other agents, such as pyrimethamine, sulfadiazine [7], clindamycin (CL) [8], azithromycin [9], or clarithromycin [5]. An experimental intravenous formulation also demonstrated high efficacy in a reactivated toxoplasmosis mouse model [10].

CL, a lincosamide-class antibiotic, targets both aerobic and anaerobic bacteria by inhibiting protein synthesis. It binds to the bacterial 50S ribosomal subunit, preventing bacterial growth. Beyond its antibacterial uses, CL has also been employed—alone or in combination—for toxoplasmosis treatment [11, 12].

The need for novel toxoplasmosis therapies remains urgent to overcome current treatment limitations, safeguard high-risk populations, and reduce the global impact of this infection. Continued research is vital to advancing therapeutic options and improving patient outcomes. To address these gaps, this study systematically evaluates the anti-parasitic efficacy of AT both as monotherapy and in combination with CL using a well-established BALB/c mouse model infected with the clinically relevant *PRU* strain o*f T. gondii*.

## 2. Materials and Methods

### 2.1. Mice

Female BALB/c mice (Razi Vaccine and Serum research Institute, Karaj, Iran) weighing 20 to 25 g at the beginning of each experiment were used. Mice were housed four to a cage and offered drinking water ad libitum.

### 2.2. Parasite

The *T. gondii PRU* strain used in this study was provided by the Parasitology Department at Mazandaran University of Medical Sciences. To establish chronic infection in BALB/c mice, the parasite tachyzoites were maintained by serial intraperitoneal passage in laboratory mice. Three chronically infected donor mice were euthanized via chloroform inhalation anesthesia and surface-sterilized in 96% ethanol. Under a biosafety hood, skulls were aseptically opened, and brains were extracted. Brain tissue was rinsed in sterile distilled water, and cysts were confirmed microscopically (400× magnification). Tissue was gently homogenized to preserve cyst integrity. The homogenized brain suspension was adjusted to 2 mL with sterile water and further dispersed using a 2.5 mL syringe. Cysts were enumerated using a Neubauer chamber to standardize the inoculum. Each mouse received an intraperitoneal injection containing 20–25 cysts. Infected mice were ear-marked, randomized into five groups, and housed individually.

### 2.3. Drugs

**CL:** Hydrochloride powder (Sepidaj Pharmaceutical Co., Iran) was administered at 400 mg/kg/day. AT: Micronized powder (Hubei Vanz Pharm Co., China) was given at 100 mg/kg/day. Doses were chosen based on prior studies demonstrating efficacy [13, 14] (400 mg CL /kg/day and 100 mg AT/kg/day). Suboptimal doses (lower doses of both drugs) were also tested to better evaluate combination therapy effects. Infrared (IR) spectroscopy was performed at Tarbiat Modares University's

Faculty of Medical Sciences to confirm drug integrity. To control for drug side effects, separate groups of animals were given CL (400 mg/kg/day) and AT (100 mg/kg/day) for 3 months, as well as AT plus CL (100 plus 400 mg/kg/day) for 2 months.

### 2.4. Experimental design

Mice were intraperitoneally inoculated with 20-25 *T. gondii* cysts and randomly divided into treatment groups (n=12 per group): 1) CL monotherapy (400 mg/kg/day); 2) AT monotherapy (100 mg/kg/day); and 3) Combination therapy (AT + CL: 100 + 400 mg/kg/day). Two control groups were included: 1) negative control (NC): uninfected mice; and 2) positive control (PC): infected, untreated mice. Following inoculation, mice were housed for 8 weeks to establish chronic infection. Treatment began 24 hours after inoculation and continued for 14 consecutive days. Survival was monitored daily throughout the experiment. The complete study was replicated three times with consistent results. Data presented represent pooled results from all replicates.

### 2.5. Bioassay

Following the 14-day treatment period, mice were euthanized using chloroform inhalation anesthesia. Under sterile biosafety cabinet conditions, mice were secured on a dissection tray, skulls were aseptically opened using surgical tools (scalpel and forceps) and whole brains were extracted and rinsed with sterile distilled water. Each brain was divided into two hemispheres, The left hemisphere was stored at -80 °C in sterile microtubes for molecular analysis and the right hemisphere was used for tissue cyst quantification. Brain hemispheres designated for cyst counting were homogenized, and 20-25 cysts from each sample were intraperitoneally inoculated into two naive mice per sample.

### 2.6. Statistical analysis.

The cyst count data were analyzed using one-way analysis of variance (ANOVA) in GraphPad Prism software (version 8), with statistical significance set at $P<0.05$. Post-hoc multiple comparisons were performed when ANOVA indicated significant differences between groups.

## 3. Results

Following the 14-day treatment regimen, quantitative analysis revealed that neither AT nor CL monotherapy achieved complete cyst eradication. All treatment groups showed statistically significant reductions in brain cyst counts compared to untreated controls (PC) ($P<0.0001$). The magnitude of cyst reduction varied by treatment regimen (Table 1 and Figure 1).

In addition, a significant variation in cyst counts was observed across all treatment groups ($P<0.0001$). AT monotherapy demonstrated superior efficacy, with significantly fewer cysts than CL monotherapy ($P<0.0001$) and combination therapy (AT + CL) ($P<0.0001$). CL monotherapy also showed reduced efficacy compared to the combination group ($P<0.0001$) (Figure 1).

AT exhibited significantly stronger anti-toxoplasmic activity than CL. The AT + CL combination paradoxically showed lower efficacy than AT alone, suggesting an antagonistic drug interaction against the *PRU* strain. No treatment-related toxicity (e.g. lethargy, weight loss) was observed during extended maintenance (2–3 months) in any drug-treated group.

## 4. Discussion

*T. gondii* exhibits limited species diversity but comprises three major strain types with distinct biological properties. Type I (e.g. RH, GT1) is highly virulent in mice, often lethal in acute infection models. Type II (e.g. PRU, ME49) is moderately virulent; it preferentially

**Table 1.** The number of cysts counted in the brains of different groups of mice after treatment with AT and CL

| Groups | Drugs used | Cyst /g in brain | P* |
|---|---|---|---|
| 1 | Atovaquone (AT) | 163.33±29.52 | 2, 3, 4 |
| 2 | Clindamycin (CL) | 496±41.85 | 1, 3, 4 |
| 3 | AT + CL | 1096.8±84.82 | 1, 2, 4 |
| 4 | No treatment for positive control (PC) | 1600.8±75.91 | 1, 2, 3 |

*Significant differences in various groups based on One-way ANOVA test.

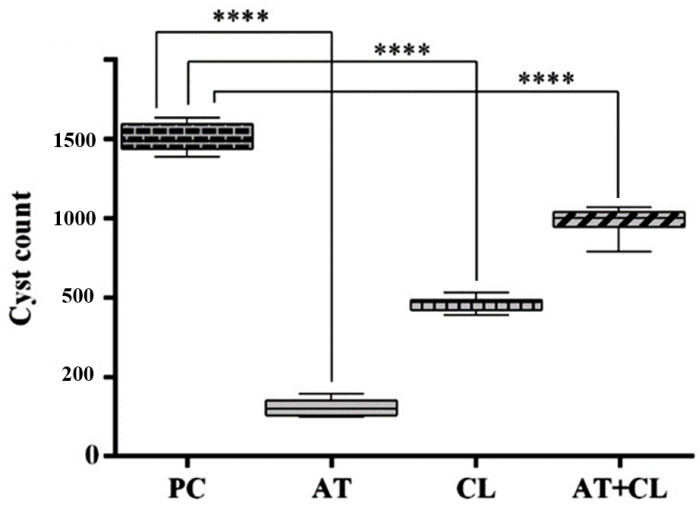


**Figure 1.** The effect of treatment with AT, CL, and the combined treatment (AT + CL) on the number of tissue cysts in the brain tissue of mice

Abbreviations: PC: Positive control (no treatment), AT: Atovaquone, CL: Clindamycin.

establishes chronic infections in intermediate hosts (including humans) and type III (e.g. CEP) has attenuated virulence and is primarily used for comparative studies [15]. As a canonical type II strain, PRU is widely employed in toxoplasmosis research due to its clinical relevance as a model for human chronic infection and cyst persistence. It is often used in laboratory studies to understand *T. gondii* biology, host-parasite interactions, and the immune response. It helps researchers investigate pathogenesis, therapeutic development, and vaccine design [16].

Toxoplasmosis represents a major public health concern due to its severe consequences for pregnant women and immunocompromised individuals. As awareness of its health impacts increases, so does the need for more effective and accessible treatments. Recent advances in our understanding o*f T. gondii* biology have uncovered promising new drug targets, including essential metabolic pathways, critical signaling mechanisms, and vulnerable stages of the parasite's life cycle that could be exploited for therapeutic development. Novel drug compounds or combination therapies may provide improved treatment outcomes through enhanced efficacy, reduced toxicity, or innovative mechanisms of action. The development of such treatments could significantly reduce cases of severe toxoplasmosis, thereby decreasing healthcare burdens and improving quality of life for affected populations [16].

The management of toxoplasmosis varies based on patient age, immune status, and clinical presentation. While most available medications effectively target the tachyzoite stage, they demonstrate limited activity against persistent tissue cysts. Naphthoquinone derivatives such as AT represent an exception, showing modest cysticidal activity in experimental models, though their clinical use has primarily been documented in HIV/AIDS patients [17]. The structural complexity of the cyst wall presents a significant therapeutic challenge.

In clinical practice, the combination of pyrimethamine with either sulfadiazine or CL remains the gold standard for both acute treatment and secondary prophylaxis [17, 18]. However, treatment-limiting toxicity frequently necessitates alternative approaches in a substantial proportion of patients.

Our experimental findings demonstrate that while neither AT nor CL monotherapy achieved complete cyst eradication in the *T. gondii PRU* strain model, both agents significantly reduced cerebral cyst burden compared to untreated controls. Notably, AT exhibited superior anti-parasitic efficacy relative to CL, with statistically significant differences in cyst reduction between the two treatment modalities.

In the study by Moshkani and Dalimi (2000), mice infected with the *T. gondii* RH strain tachyzoites were treated with AT and azithromycin, either alone or in combination. The results showed dose-dependent survival rates with AT monotherapy: 8%, 17%, and 25% of mice survived at doses of 20, 50, and 100 mg/kg/day, respectively. While azithromycin failed to eradicate the parasite from either brain or visceral tissues, AT demonstrated complete clearance of visceral infection at all

tested doses (20-100 mg/kg/day) and eliminated brain infection at the highest dose (100 mg/kg/day). Notably, combination therapy with AT and azithromycin showed neither synergistic nor additive effects and failed to achieve complete parasite eradication in any tissue compartment [9].

Djurkovic-Djakovic et al. (1999) evaluated the efficacy of CL combined with AT in a murine model of acute toxoplasmosis. Swiss Webster mice were intraperitoneally infected with either $10^2$ or $10^4$ tachyzoites of the *T. gondii* RH strain and received oral treatment with each drug alone or in combination for 14 days starting from day 1 post-infection, with survival monitored over 7 weeks. In mice infected with $10^2$ parasites, the drug combination significantly improved survival compared to AT monotherapy, though it provided no additional benefit over CL alone, which showed strong efficacy. For the higher inoculum ($10^4$ parasites), the combination therapy outperformed AT alone at both low and high doses but again showed no advantage over CL monotherapy [8].

In a follow-up study in 2002, the same research group examined this drug combination against the ME49 strain in Swiss-Webster mice orally infected with 10 or 20 cysts. Treatment with AT (5–100 mg/kg/day) and CL (25–400 mg/kg/day), either alone or combined, was administered for 2–4 weeks. In acute infection, all treatments significantly enhanced survival and reduced brain cyst burden, with AT-containing regimens (both monotherapy and combination) showing superior cyst reduction compared to CL alone. For chronic infection, only the combination therapy achieved a significant decrease in cyst burden when assessed 2 weeks post-treatment [19].

Several studies have evaluated AT's effectiveness against toxoplasmosis in various animal models. In hamsters with acute acquired Toxoplasma retinochoroiditis, systemic AT monotherapy demonstrated comparable efficacy to standard regimens (pyrimethamine-sulfadiazine, CL, and spiramycin) in reducing Toxoplasma brain cyst burden during acute infection. Notably, AT also significantly decreased cyst numbers in chronic infection [20].

Formulation advancements have enhanced AT's therapeutic potential. Azami et al. (2018) developed an AT nanoemulsion that showed improved bioavailability and tissue distribution in mice infected with both RH and Tehran *T. gondii* strains. This formulation increased survival time while reducing parasitemia, brain cyst count, and cyst size [21]. More recently, Goudarzi et al. (2024) demonstrated that AT-loaded exosomes (EXO-ATQ) achieved a 97.3% cyst reduction in chronic infection (Tehran strain) and showed enhanced efficacy against tachyzoite proliferation in vitro compared to conventional AT suspension [22].

Beyond treatment, AT shows promise for toxoplasmosis prophylaxis in transplant recipients, though its safety and efficacy in this specific population require further investigation [4, 23].

## 5. Conclusion

Collective research findings position AT as a promising therapeutic candidate against *T. gondii*, demonstrating superior cyst-reducing efficacy compared to conventional therapies. Its potential integration into future treatment protocols is further supported by evidence that combination regimens can significantly enhance therapeutic outcomes. These advances are particularly critical given toxoplasmosis' growing public health burden, especially among immunocompromised individuals and pregnant women, underscoring the urgent need for continued investigation into parasite biology and host-pathogen dynamics.

While pyrimethamine-sulfadiazine remains the current standard of care, its limitations—including treatment-limiting toxicity and incomplete cyst eradication—necessitate the development of safer, more effective alternatives. A multidisciplinary approach combining parasitology, drug development, and clinical research will be essential to advance next-generation therapies. Such innovations must address the full spectrum of toxoplasmosis management, from acute infection to chronic cyst clearance, ultimately improving therapeutic efficacy and patient quality of life.

### Acknowledgements

The authors of this article would like to thank all the staff of the Department of Parasitology, Faculty of Medical Sciences, Tarbiat Modares University, for their assistance.

### Compliance with ethical guidelines

This study was approved by the Ethics Committee of Tarbiat Modares University, Tehran, Iran (Code: IR.MODARES.REC.1400.117).

### Funding

This study was extracted from the PhD dissertation of Nima Zouei, approved by the Department of Parasitol-

ogy, Faculty of Medical Sciences, Tarbiat Modares University, Tehran, Iran. This study was financially supported by Tarbiat Modares University, Tehran, Iran (Grant No.: MED 87650).

## Authors' contributions

Conceptualization, study design, and writing the original draft: All authors; Data acquisition, analysis and data interpretation: Nima Zouei; Statistical analysis, project administration, technical, and material support, review and editing: Abolhossein Dalimi.

## Conflict of interest

The authors declared no conflict of interest.

## Data availability

The data used to support the findings of this study are available from the corresponding author upon reasonable request.

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