In Vitro Amoebicidal Activity of Titanium Dioxide/UV-A Combination Against Acanthamoeba

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Acanthamoeba of the Acanthamoeba genus are free-living, aerobic, eukaryotic organisms and are widely dispersed in nature and can inhabit terrestrial and aquatic environments.1 Acanthamoeba species present two morphologic stages in their life cycle: a vegetative trophozoite stage, in which there is reproduction by binary fission, and a cyst stage that is resistant to environmentally adverse conditions.2 Acanthamoeba protozoan are involved in keratitis and encephalitis.3 Acanthamoeba keratitis is a medical emergency.4 The main risk factors are contact lens wearing and corneal trauma.5 The pathogenesis is characterized by two events: (1) trophozoites adhere to the epithelial surface and invade then degrade the stromal extracellular matrix6 and (2) encystment of the protozoan, which promotes resistance and recurrence of infection.7 Currently, the treatment involves topical antimicrobials, such as chlorhexidine, polyhexamethylene biguanide,8 diamidines,9 and antifungal agents10 belonging to membrane-acting agents.11 Contrary to bacterial or fungal keratitis, failure of topical therapy is common.9 Based on the severity of Acanthamoeba keratitis and as a last resort, the only viable surgical option is penetrating keratoplasty.12 Among the novel therapeutic approaches, corneal cross-linking seems promising in the management of Acanthamoeba keratitis.13,14 Miltefosine (hexadecylphosphocholine), an alkylphosphocholine, showed interesting results too, in topical15 and systemic therapy.16 The development of antiacanthamoebic agents remains a challenge in order to improve the visual prognosis of the disease.

Titanium dioxide (TiO2) is a fine crystal powder. There are two forms of TiO2: micro particles, widely used in surface coatings and cosmetic materials, and nanoparticles. TiO2 nanoparticles have photocatalytic activity17: they produce oxygenated free radicals under UV-A radiation. Oxygenated free radicals cause cell lysis by lipid peroxidation,18 release of intracellular components,19 and nucleic acid20,21 and protein damage.22,23 TiO2 antimicrobial activity is known and commonly used as a self-disinfecting surface option.17 TiO2 is used in number of materials, including health care items.24

The antimicrobial properties of some types of nanoparticles, mainly metallic ones, have been recently demonstrated in vitro, notably against Gram-negative and Gram-positive bacteria.25 This study presents results of a series of in vitro experiments evaluating the amoebicidal effects of TiO2 with UV-A on Acanthamoeba cysts and trophozoites in an effort to ultimately expand the armamentarium of antimicrobial agents for the treatment of amoebic keratitis.

Methods
Acanthamoeba Strains
Two Acanthamoeba strains were selected from a panel of human clinical ocular amoebic pathogens isolated by corneal scraping from patients with severe amoebic keratitis and

Keywords: Acanthamoeba, cornea, infection, titanium dioxide, ultraviolet rays

Purpose. To assess the amoebicidal effect of titanium dioxide (TiO2)/UV-A combination against Acanthamoeba sp trophozoites and cysts.

Methods. The amoebicidal effect of the TiO2/UV-A combination was tested on trophozoites and cysts of clinical isolates of Acanthamoeba baileyi and Acanthamoeba sp genotype T4, obtained from two severe cases of ulcerative keratitis. Samples of cultured Acanthamoeba were transferred to a 96-well plate. We tested the effect of sterile water (blank control), TiO2 alone, UV-A alone, TiO2 and additional UV-A exposure, chlorhexidine 0.02% alone, chlorhexidine 0.02% and TiO2, chlorhexidine and UV-A, chlorhexidine 0.02% and TiO2, and additional UV-A exposure. Cell viability assessment was done using the trypan blue dye exclusion method.

Results. The combination of TiO2 with UV-A demonstrated antitrophozoite and anticyst activity (P < 0.05). This in vitro study showed a synergistic effect of the association of chlorhexidine with TiO2 and UV-A on cysts (P < 0.001).

Conclusions. Given the in vitro synergistic effectiveness of the association of chlorhexidine with TiO2 and UV-A against cysts, the treatment of Acanthamoeba keratitis could be improved by this new therapeutic approach.
identified using the routine procedure (PCR) of the parasitology laboratory. The pathogens were one isolate of *Acanthamoeba* sp belonging to T4 genotype (*Acanthamoeba T4*) and one of *Acanthamoeba castellanii*.

**Acanthamoeba Axenization Assay**

Briefly, the amoeba was isolated from corneal tissue by plate culture procedure onto an nonnutrient agar medium covered with an avirulent, plasmid-less, heat-inactivated *Escherichia coli* strain without antibiotic resistance at 25°C. A piece of agar culture was picked up aseptically from nonnutrient agar medium and transferred to a tissue culture flask (Dutscher, Brumath, France) containing 5 ml of peptone-yeast extract glucose (PGY) broth medium with penicillin-streptomycin to proceed with the axenization process of primary isolation.

For trophozoites, after 48 hours of incubation at 35°C, the excystment process was observed followed by the growth of trophozoites in monolayer. Trophozoites were harvested by washing in diluted saline solution twice by centrifugation at 405g for 10 minutes. The washing process was followed by cell counting and quantitative standardization of both the total and viable trophozoites, determined with trypan blue (Corning, New York, NY, USA) staining. The experimental viable trophozoites concentration was adjusted to $1 \times 10^5$ trophozoites/mL.

For cysts, after 48 hours of incubation at 35°C, the excystment process was observed followed by growth of trophozoites in monolayer. Cell supernatants were discarded, and the encystment of adherent trophozoites was performed in fresh PGY medium culture. Viable cysts were harvested and washed in diluted saline solution twice by centrifugation at 405g for 10 minutes. The washing process was followed by cell counting and quantitative standardization of both the total and viable cysts, determined with trypan blue staining. The experimental viable cyst concentration was adjusted to $1 \times 10^5$ cysts/mL. For each trial, the count of the chambers was performed in triplicate.

**Titanium Dioxide**

The TiO$_2$ eye drop solution was prepared by the pharmacy department (Hôpitaux Universitaires de Strasbourg, France) by dissolving titanium powder (Inresa, Bartenheim, France; conformed to European pharmacopeia standard 9.2) in saline water and carbomer gel (Gel Larmes; Théa, Clermont-Ferrand, France) at a 0.8-mg/mL final concentration. This final concentration was chosen because of imperatives of fabrication (it was the highest final concentration that can be produced)$^{27}$ and the potential efficacy of TiO$_2$ eye drops with UV-A. This potential efficacy was evaluated by oxygenated free radical production measured by chemiluminescence. Briefly, chemiluminescence is based on photon emission when an excited molecule returns to its lowest energy state.$^{28}$ Luminol (97%; Sigma-Aldrich Chimie, Saint-Quentin-Fallavier, France) produces photons in attendance of oxygenated free radicals.$^{29}$ The photon production is measured by a luminometer (Glomax 96 Microplate Luminometer; Promega, Madison, WI, USA), and chemiluminescence is expressed in related light unit (RLU). We tested the production of oxygenated free radicals by TiO$_2$ eye drop at final concentrations of 0.2, 0.4, and 0.8 mg/mL with and without irradiance of UV-A for 30 minutes. The experiment was repeated three times. There was minimal chemiluminescence without UV-A. The result of the three concentrations with UV-A is represented in the Figure.

**In Vitro Testing**

To begin with, we tested the in vitro effect of TiO$_2$ with UV-A exposure on trophozoites (*Acanthamoeba T4*, then *Acanthamoeba castellanii*). The second step was the in vitro test on cysts (*Acanthamoeba T4* then *Acanthamoeba castellanii*).

Eight groups were tested as follows: sterile water (blank control), TiO$_2$ alone (T), UV-A alone (UV-A), TiO$_2$ and additional UV-A exposure (T+UV-A), chlorhexidine 0.02% alone (C; Gilbert, Herouville-Saint-Clair, France), chlorhexidine 0.02% and TiO$_2$ (C+T), chlorhexidine 0.02% and UV-A (C+UV-A), and chlorhexidine 0.02% and TiO$_2$ with additional UV-A exposure (C+T+UV-A). Each group was assayed in triplicate.

An aliquot of 30 μL of an *Acanthamoeba*-containing solution was placed into each well of a sterile 96-well microplate (Dutscher). We used three wells for each group. For a blank control, 30 μL of saline solution was added. For the TiO$_2$ groups (T and T+UV-A) 30 μL of the TiO$_2$ eye drop was added (with a final concentration of 0.8 mg/mL). For the chlorhexidine groups (C and C+UV-A), 30 μL of chlorhexidine was added (with a final concentration of 0.2 mg/mL, clinical concentration). For the chlorhexidine and TiO$_2$ groups (C+T and C+T+UV-A), 15 μL of the TiO$_2$ eye drop (with a final concentration of 0.8 mg/mL) and 15 μL of chlorhexidine (with a final concentration of 0.2 mg/mL) was added. Irradiance of UV-A light source with a 365-nm wavelength at a power of 0.8, 0.4, and 0.2 mW/cm$^2$ was used.

**FIGURE.** Chemiluminescence (in related light unit, RLU) of different concentrations of TiO$_2$ eye drop with UV-A light.

![Graph showing chemiluminescence](image-url)
density of 2.2 mW/cm² was dispensed on the four groups with UV-A exposure for 30 minutes. For cysts, based on the classical clinical treatment regimen, we retreated after 24 hours, following the same steps.

### Analysis of Tests

After the 24-hour incubation period for trophozoites and the 48-hour incubation period for cysts, the cell viability of each assay was measured with the trypan blue dye exclusion method in a counting chamber (Dutscher) under microscope trypan blue stain. Trypan blue is a vital stain that colors only dead cells. Living amoebae have a refringent appearance under light microscopy, whereas dead amoebae exhibit a blue color (see Supplementary Fig. 1 for photographs of live and dead trophozoites and cysts).

### Statistical Analysis

The analysis focuses on the following *Acanthamoeba* outcomes: trophozoites persist, die, or encyst; and cysts persist or die. Descriptive statistics were expressed as the mean and standard deviation (SD) of the triplicate of the three repeats. The 2-way ANOVA test was used for the analysis, assuming a standard deviation (SD) of the triplicate of the three repeats. Descriptive statistics were expressed as the mean and standard deviation (SD) of the triplicate of the three repeats. Significant differences. A P < 0.05 was considered statistically significant.

### RESULTS

Regarding *Acanthamoeba T4* trophozoites (Table 1), after 24 hours of incubation, the combination of TiO₂ and UV-A demonstrated antitrophozoite activity: the difference between the control group and the TiO₂+UV-A group was statistically significant (P < 0.001). Each group with chlorhexidine (versus control) was an amebicide (P > 0.001). All the trophozoites died in the presence of chlorhexidine.

Regarding *Acanthamoeba batchetti* trophozoites (Table 1), after 24 hours of incubation, the in vitro experiment showed no difference among the groups UV-A, TiO₂ alone, and TiO₂+UV-A: UV-A versus control (P > 0.05), TiO₂ versus control (P > 0.05), and TiO₂+UV-A versus control (P > 0.05). The encystment was statistically lower in the TiO₂+UV-A group than in the control group (P < 0.05). Each group with chlorhexidine (versus control) was an amebicide (P > 0.001).

Regarding *Acanthamoeba T4* (Table 2) and *Acanthamoeba batchetti* (Table 2) cysts, after 48 hours of incubation, the in vitro experiment showed no difference among the groups UV-A and TiO₂ alone: UV-A versus control (P > 0.05) and TiO₂ versus control (P > 0.05). TiO₂+UV-A had the following an

### Table 1. Percentage of Trophozoite Viability and Percentage of Encystment at 24 hours*

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Trophozoite Viability</th>
<th>Encystment</th>
<th>Trophozoite Viability</th>
<th>Encystment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>48 ± 20</td>
<td>&gt;0.05</td>
<td>47 ± 18</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>UV-A</td>
<td>52 ± 13</td>
<td>&gt;0.05</td>
<td>44 ± 14</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>TiO₂</td>
<td>45 ± 16</td>
<td>&gt;0.05</td>
<td>19 ± 8</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>TiO₂ and UV-A</td>
<td>34 ± 13</td>
<td>&lt;0.05</td>
<td>17 ± 17</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C</td>
<td>0 ± 0</td>
<td>&lt;0.001</td>
<td>0 ± 0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C+TiO₂</td>
<td>0 ± 0</td>
<td>&lt;0.001</td>
<td>0 ± 0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C+UV-A</td>
<td>0 ± 0</td>
<td>&lt;0.001</td>
<td>0 ± 0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C+TiO₂+UV-A</td>
<td>0 ± 0</td>
<td>&lt;0.001</td>
<td>0 ± 0</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

* P values are comparisons between control and each condition. Significant P values are in bold. Means and SD from triplicate experiments are shown.
† UV-A, 30 minutes of initial exposure, 365-nm wavelength, at a power density of 2.2 mW/cm²; TiO₂ eye drop at 0.8 mg/ml final concentration; C, Chlorhexidine eye drop at 0.2 mg/ml final concentration.

### Table 2. Percentage of Cyst Viability of *Acanthamoeba T4* and *Acanthamoeba batchetti* at 48 hours*

<table>
<thead>
<tr>
<th>Treatment†</th>
<th>Acanthamoeba T4</th>
<th>Acanthamoeba batchetti</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cyst Viability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean ± SD, %</td>
<td>P value</td>
</tr>
<tr>
<td>Control</td>
<td>94 ± 6</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>UV-A</td>
<td>95 ± 5</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>TiO₂</td>
<td>85 ± 5</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>TiO₂ and UV-A</td>
<td>51 ± 15</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C</td>
<td>27 ± 12</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C+TiO₂</td>
<td>22 ± 16</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C+UV-A</td>
<td>21 ± 19</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C+TiO₂+UV-A</td>
<td>11 ± 16</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean ± SD, %</td>
<td>P value</td>
</tr>
<tr>
<td>Control</td>
<td>97 ± 5</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>UV-A</td>
<td>100 ± 0</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>TiO₂</td>
<td>88 ± 8</td>
<td>&gt;0.05</td>
</tr>
<tr>
<td>TiO₂ and UV-A</td>
<td>69 ± 15</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C</td>
<td>39 ± 9</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C+TiO₂</td>
<td>56 ± 12</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C+UV-A</td>
<td>38 ± 9</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>C+TiO₂+UV-A</td>
<td>25 ± 6</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

* Retreatment at 24 hours.
† UV-A, 30 minutes of initial exposure, 365-nm wavelength, at a power density of 2.2 mW/cm²; TiO₂ eye drop at 0.8 mg/ml final concentration; C, Chlorhexidine eye drop at 0.2 mg/ml final concentration.
‡ P values are comparisons between control and each condition. Significant P values are in bold. Means and SD from triplicate experiments are shown.
amoebicidal effects: on Acanthamoeba T4, there were 49% of
dead cysts with TiO₂ + UV-A against 6% with control (P < 0.001); and on Acanthamoeba batchetti, there were 31% of
dead cysts with TiO₂ + UV-A against 3% with control (P < 0.001). TiO₂+UV-A was better than TiO₂ alone (P < 0.001).
Each group with chlorhexidine was better than the control (P < 0.001). There was a synergistic effect of chlorhexidine with
TiO₂+UV-A: after 48 hours, the percentage of dead cysts was
higher with the combination of C+TiO₂+UV-A than with chlorhexidine alone and on Acanthamoeba T4 cysts (P < 0.05) as on Acanthamoeba batchetti cysts (P < 0.01).

**DISCUSSION**

The work outlined here is directed to the development of TiO₂
and UV-A as a new adjunctive method for the treatment of Acanthamoeba keratitis, which is a cause of significant
morbidity worldwide and can cause rapid and devastating
vision loss. Acanthamoeba keratitis continues to be difficult
to treat despite the use of topical agents and adjunctive surgery, such as corneal transplantation. Many studies worked on the
photocatalytic utility of TiO₂/UV in a disinfection system, with
efficacy on bacteria, fungi, and viruses. Sökmen et al. used
TiO₂ for photocatalytic disinfection of Giardia intestinalis and
Acanthamoeba castellanii cysts in water with UV-C exposure.
Imran et al. synthesized TiO₂ nanoparticles and demonstrated their inhibitor effects on Acanthamoeba castellani cysts in vitro and demonstrated their inhibitor effects on Acanthamoeba castellani trophozoite growth and viability. The antimicrobial
effect of photocatalyst is a reason why we tested TiO₂ with UV-A on cysts and trophozoites of Acanthamoeba batchetti and T4 in vivo.

Acanthamoeba keratitis has been characterized as a painful
and vision-threatening disease. The infection cascade starts
with the adhesion of protozoa to the corneal surface, and the
infection involves the invasion and destruction of the corneal
stroma. In our study, we demonstrated an antiprotozoan effect of the combination of TiO₂ and UV-A. Nevertheless, the
usual treatment by chlorhexidine is better than TiO₂ with UV-A exposure. In the in vitro experiment, most of the trophozoites
died after 24 hours in the presence of chlorhexidine. The antiprotozoan activity of chlorhexidine is known. Chlorhexidine is a polyhexamethylene biguanide compound that is
positively charged and ionic with the negatively charged plasma membrane of the parasite, resulting in structural and
permeability changes, ionic leakage, cytoplasmic disruptions
causing cellular damage, and cell death.

The encysted stage is the second step of Acanthamoeba
keratitis after the adhesion and multiplication of the tropho-
zoite. Acanthamoeba cysts are composed of an ectocyst, an
external cellular layer, and an endocyst, an internal fibrillar
layer, which together provide amoebic resistance to physical
and chemical compounds. Cyst persistence in tissue is
common and a recurrence of infection can follow prolonged
topical therapy or surgical therapy. We suspect that lipid
peroxidation, release of intracellular components, and
nucleic acid are the photocatalytic effects on cysts of the TiO₂/UV-A combination, as described by bacterial (E. coli) studies. The cystoplastic membrane damage
due to chlorhexidine may facilitate entry into the cysts of
oxygenated free radicals and could explain the synergistic
effect of chlorhexidine and TiO₂ with UVA observed in vitro on
cysts. Another theory is that there was a conjugation between
chlorhexidine and TiO₂ and, thus, nanoparticles of TiO₂
facilitated chlorhexidine driving to the site of action. The
conjugation of chlorhexidine with gold nanoparticles has
produced a significant increase in its amoebicidal and
cystidal potency, with minimal associated host-cell cytoxicity.

Results obtained in vitro do not always correlate with in
vivo efficacy; therefore, further tissue culture models and
animal studies are under way to test the efficacy of this
treatment for infectious keratitis.

Furthermore, it was important to determine the cytotoxicity
of TiO₂. Eom et al. evaluated the effect of TiO₂ nanoparticle
exposure on the ocular surface in vivo on 40 rabbits. Of the five toxicity criteria, two increased after TiO₂ exposure. Given that we were able to demonstrate in vitro
activity of the TiO₂/UV-A against Acanthamoeba, it is
necessary to establish safety with other in vivo tests on corneal
epithelia cells and animal studies.

In conclusion, the combination TiO₂+ UV-A presents
antitrophozoite and an adjunctive anticyst activity in vitro
when applied with the parameters used in the present study.

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**References**


