Acanthamoebae are free-living amoebae found in the environment, including soil, freshwater, brackish water, seawater, hot tubs, and Jacuzzis. Acanthamoeba species can cause keratitis, a painful vision-threatening infection of the cornea, and fatal granulomatous encephalitis in humans. More than 20 species of Acanthamoeba belonging to morphological groups I, II, and III distributed in 15 genotypes have been described. Among these, Acanthamoeba castellanii, A. polyphaga, and A. hachetti are frequently identified as causing Acanthamoeba keratitis (AK). Improper contact lens care and contact with nonsterile water while wearing contact lenses are known risk factors for AK. During a recent multistate outbreak, AK was found to be associated with the use of Advanced Medical Optics Complete MoisturePlus multipurpose contact lens solution, which was hypothesized to have had insufficient anti-Acanthamoeba activity. As part of the investigation of that outbreak, we compared the efficacies of 11 different contact lens solutions against cysts of A. castellanii, A. polyphaga, and A. hatchetti (the isolates of all species were genotype T4), which were isolated in 2007 from specimens obtained during the outbreak investigation. The data, generated with A. castellanii, A. polyphaga, and A. hatchetti cysts, suggest that the two contact lens solutions containing hydrogen peroxide were the only solutions that showed any disinfection ability, with 0% and 66% growth, respectively, being detected with A. castellanii and 0% and 33% growth, respectively, being detected with A. polyphaga. There was no statistically significant difference in disinfection efficacy between the 11 solutions for A. hatchetti.

Acanthamoebae, which are free-living amoebae, occur worldwide in soil and water. It has been isolated from ponds, lakes, brackish water, and seawater; filters of heating, ventilating, and air-conditioning units; medical equipment, such as gastric wash tubing, dental irrigation units, contact lenses, and contact lens solutions; as well as vegetables, cell cultures, and even human and animal tissues (7, 23, 39). It has also been isolated from toxic waste dumpsites with high levels of pesticides, herbicides, pharmaceuticals, heavy metals, and polychlorinated biphenyls (35). Acanthamoeba species have two stages in their life cycle: a vegetative or trophozoite stage that reproduces by binary fission and that feeds voraciously on the bacteria and detritus present in the environment and a nondividing, cyst stage that is resistant to environmental stress. Acanthamoeba amoebae cause different types of human disease, including central nervous system infections (granulomatous amebic encephalitis, cutaneous infections) Acanthamoeba dermatitis, and ocular infections (Acanthamoeba keratitis [AK]). Granulomatous amebic encephalitis and cutaneous infections principally occur in immunocompromised individuals, including patients with human immunodeficiency virus infection or AIDS (17, 23, 37, 43). In contrast, AK principally occurs in immunocompetent individuals. AK is a painful vision-threatening infection, which, if it is not treated promptly, may lead to ulceration of the cornea, a loss of visual acuity, and, eventually, blindness (7, 15, 16). AK is associated with trauma to the cornea and with contact lens wear as a result of poor lens care and hygiene. When introduced into the eye by a contaminated contact lens, Acanthamoeba amoebae may adhere to the corneal surface and subsequently infiltrate the stoma and cause tissue damage (10). Both Acanthamoeba cysts and trophozoites can be isolated by culture from corneal scrapings or biopsy specimens and from contact lens paraphernalia (23, 43). Confocal microscopy has been used as an aid for the diagnosis of AK (29). Molecular techniques such as real-time PCR assays have been developed for the identification of Acanthamoeba species (32, 33). Sequencing analysis of the 18S rRNA gene has been used to identify as many as 15 genotypes of Acanthamoeba, of which the T4 genotype appears to be the most common in the environment and in patients with AK (2, 23).

The first documented case of AK in the United States occurred in 1973 in a south Texas rancher following trauma to his right eye (15, 40, 42). Both trophozoite and cyst stages of Acanthamoeba polyphaga were demonstrated in corneal sections. Between October 1985 and August 1986, Stehr-Green et al. (41) conducted a case-control study to investigate an outbreak of AK in the United States. The majority of case patients wore contact lenses, and illness was most commonly associated with the use of homemade saline solutions and lens care practices, such as the disinfection of the lenses less frequently than recommended and swimming while wearing contact lenses (8, 41). Contact lens use is now considered an important risk factor for AK in the United States. AK cases have continued to be diagnosed since the 1986 outbreak, but because AK is not a reportable disease in the United States, the actual number of cases occurring each year is not known.
A recent study indicated a dramatic increase in the number of AK cases in the Chicago, IL, area (16). An investigation conducted by the Centers for Disease Control and Prevention (CDC) revealed that this increase in the number of AK cases was occurring nationwide, starting in 2004 and continuing through 2007 (7). A subsequent investigation identified the use of Advanced Medical Optics (AMO) Complete MoisturePlus multipurpose contact lens solution as the primary risk factor, leading to an international recall of this product by the manufacturer (7, 16). We therefore decided to examine this and other frequently used major contact lens solutions for their efficacies against *Acanthamoeba* species isolated from clinical samples collected during the 2007 AK outbreak investigation.

### MATERIALS AND METHODS

**Isolation of Acanthamoeba.** During the 2007 AK outbreak investigation, 94 specimens from patients were collected and cultured on nonnutrient agar plates coated with a layer of *Escherichia coli*. In the 24 plates that were positive, the amoeba consumed the bacteria, multiplied, and encysted after most of the bacteria were gone. Both trophozoites and cysts were examined microscopically to confirm that amoebae were present, and were assigned to morphological group II. In addition, cyst morphology was studied and the presence of trophozoites and the efficacies of the solutions were recorded as positive or negative.

**Contact lens solutions.** Eleven different contact lens solutions were tested: Alcon Opti-Clean II, Alcon Opti-Free Express, Alcon Opti-Free RepleniSH, AMO Complete MoisturePlus, AMO UltraCare, Bausch & Lomb Boston Simplus, Bausch & Lomb ReNu MoistureLoc, Bausch & Lomb ReNu MultiPlus, Ciba Vision Clear Care, Ciba Vision AQuify, and Kirkland Signature Multipurpose Solution. These 11 solutions were selected for this study because they were brands used by case patients in the 2004 to 2007 AK outbreak. Ten of the 11 solutions were purchased from retail stores in the Atlanta, GA, area. The remaining solution, Bausch & Lomb ReNu MoistureLoc, was removed from the market in 2006 because it was the brand of multipurpose contact lens solution associated with an outbreak of *Fusarium* keratitis (9). This solution was provided by colleagues at CDC who had kept a supply of this solution following the investigation of the *Fusarium* keratitis outbreak. The solutions used in this study, along with their active ingredients and disinfectant properties, are listed in Table 1.

To study the effects of various contact lens solutions against the cysts of the three species of *Acanthamoeba*, the amoeba were grown on agar plates for 3 weeks with *E. coli*. When most of the bacteria were consumed, trophozoites began to differentiate into cysts, and by the third week, the agar plates were covered with cysts. Cysts were harvested from the agar plates, washed three times, and incubated at 24°C for either 4 or 6 h (according to the manufacturers' contact lens soaking time recommendations) and for 24 h.

The two hydrogen peroxide-containing solutions (AMO UltraCare and Ciba Vision Clear Care) require the use of lens cases, provided in the box, that need to be filled with the contact lens solution to the fill line. Therefore, 10 μl of the cyst-containing solution was added to 1 ml of each contact solution (Alcon Opti-Clean II, Alcon Opti-Free Express, Alcon Opti-Free RepleniSH, AMO Complete MoisturePlus, Bausch & Lomb Boston Simplus, Bausch & Lomb ReNu MoistureLoc, Bausch & Lomb ReNu MultiPlus, Ciba Vision AQuify, and Kirkland Signature Multipurpose Solution) in 15-ml tubes, in triplicate, and incubated at 24°C for either 4 or 6 h (according to the manufacturers' contact lens soaking time recommendations) and for 24 h.

### Table 1. Contact lens solutions tested and their ingredients

<table>
<thead>
<tr>
<th>Contact lens Solution</th>
<th>Active ingredient(s)</th>
<th>Other ingredients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alcon Opti-Clean II</td>
<td>PolyQuad (0.001%)</td>
<td>Tween 21, MicroClens, edetate disodium (0.1%)</td>
</tr>
<tr>
<td>Alcon Opti-Free Express</td>
<td>PolyQuad (0.001%), Aldox (0.0005%)</td>
<td>Sodium citrate, sodium chloride, boric acid, sorbitol, AMP-95, Tetronic 1304, edetate disodium (0.05%)</td>
</tr>
<tr>
<td>Alcon Opti-Free RepleniSH</td>
<td>Polypropylene glycol, PolyQuad (0.001%), Aldox (0.0005%)</td>
<td>Sodium citrate, sodium chloride, sodium borate, TeaGlyde, Tetronic 1304, nonanonyl ethylenediaminetriacetic acid</td>
</tr>
<tr>
<td>AMO Complete MoisturePlus</td>
<td>Polyhexamethylene biguanide (0.0001%), Poloxamer 237</td>
<td>Hydroxypropyl methylcellulose, propylene glycol, phosphate, ta urine, edetate disodium, sodium chloride, potassium chloride, water</td>
</tr>
<tr>
<td>AMO UltraCare*</td>
<td>Hydrogen peroxide (3%)</td>
<td>Sodium stannate, sodium nitrate; buffered with phosphates and water</td>
</tr>
<tr>
<td>Bausch &amp; Lomb Boston Simplus</td>
<td>Chlorhexidine gluconate (0.003%), polyaminopropyl biguanide (0.0005%)</td>
<td>Poloxamine, hydroxypropylphosphate, boric acid, sodium borate, sodium chloride, hydroxypropylcellulose, Glucam</td>
</tr>
<tr>
<td>Bausch &amp; Lomb ReNu MoistureLoc</td>
<td>Alexidine (0.00045%)</td>
<td>Boric acid, sodium chloride, sodium phosphate, hydranate, poloxamine, MoistureLoc</td>
</tr>
<tr>
<td>Bausch &amp; Lomb ReNu MultiPlus</td>
<td>Dymed (polyaminopropylbiguanide; 0.0001%)</td>
<td>Hydranate, boric acid, edetate disodium, poloxamine, sodium borate, sodium chloride, hydrogenperoxide-buffered system, Phuronic 17R4, Sorbitol, tromethamine, pluronic F127, sodium phosphate, dihydrogen, dexamethasone, edetate disodium dehydrate</td>
</tr>
<tr>
<td>Ciba Vision Clear Care*</td>
<td>Hydrogen peroxide (3%)</td>
<td>Poloxamine, Hydrogen peroxide (3%), Pullulan, Poloxamer 407, PEG-30-ethanol, PEG-30, Brij-78, sodium borate, sodium chloride, sodium phosphate, taurine, Bocamid, phosphate, taurine, edetate disodium, sodium chloride, Potassium chloride, water</td>
</tr>
<tr>
<td>Ciba Vision AQuify</td>
<td>Polyhexanide (0.001%)</td>
<td>Poloxamer 237, edetate disodium, sodium chloride, potassium chloride, water</td>
</tr>
</tbody>
</table>

* Hydrogen peroxide-containing solution.
lens solutions, controlling for the three *Acanthamoeba* species, at 4 to 6 h and 24 h of incubation. Fisher’s exact test was used to compare the number of plates positive for each species. All analyses were performed with SAS (version 9.1) software (SAS Institute Inc., Cary, NC). Statistical significance was set at an alpha level of 0.05.

**RESULTS**

Of the 11 contact lens solutions that were examined for their efficacies in inactivating cysts of the three *Acanthamoeba* species, one of these solutions that contained hydrogen peroxide (Ciba Vision Clear Care) demonstrated the greatest inactivation of cysts of all three species of *Acanthamoeba* (Table 2). Overall, there were no statistically significant differences in the susceptibilities of the three *Acanthamoeba* species to the contact lens solutions tested. All three species were the most responsive to the Ciba Vision Clear Care solution, which was the only solution that prevented excystation under the experimental conditions used in this study.

Considering all *Acanthamoeba* species together, there were statistically significant differences in the efficacies of the different brands of contact lens solutions at both 4 to 6 h ($P < 0.0001$) and 24 h ($P < 0.0001$) of incubation. At 4 to 6 h of incubation, there were statistically significant differences in disinfection efficacy between the 11 solutions for *A. castellanii* ($P = 0.008$) and *A. polyphaga* ($P = 0.0014$). Specifically, the Ciba Vision Clear Care and AMO UltraCare solutions, both of which contained hydrogen peroxide, were the only solutions that showed any disinfection ability, showing 0% and 66% growth, respectively, for *A. castellanii* and 0% and 33% growth, respectively, for *A. polyphaga*. There was no statistically significant difference in disinfection efficacy between the 11 solutions for *A. hatchetti*. Overall, the differences in the efficacies of the solutions between species at 4 to 6 h incubation were not significant with *A. castellanii*, *A. polyphaga*, and *A. hatchetti*, for which 87.9% (29/33), 84.9% (28/33), and 90.9% (30/33) of the plates were positive, respectively.

At 24 h of incubation, there were statistically significant differences in disinfection efficacies between the 11 solutions for *A. castellanii* ($P = 0.0081$) and *A. hatchetti* ($P = 0.0264$) but not *A. polyphaga*. In addition to the Ciba Vision Clear Care and AMO UltraCare solutions, several non-hydrogen peroxide-containing solutions also showed some disinfection ability at 24 h of incubation (Tables 2 and 3). Overall, the differences in the efficacies of the solutions against the species at 24 h of incubation were not significant for *A. castellanii*, *A. polyphaga*, and *A. hatchetti*, for which 81.8% (27/33), 69.7% (23/33), and 78.8% (26/33) of the plates were positive, respectively.

**DISCUSSION**

Contact lens wear is the most common risk factor for the development of AK in the United States: 85% of cases occur in contact lens wearers (30). Studies demonstrate that nearly all rigid and soft contact lens solutions sold in the United States have inadequate *Acanthamoeba* disinfection efficacy (1, 3, 4, 5, 12, 13, 14, 16, 19, 20, 25, 26, 37, 39).

The two most common types of solution used for contact lens disinfection are (i) the multipurpose solution, in which a single solution is used for cleaning, disinfecting, and storing the lenses, and (ii) the hydrogen peroxide-based system, in which either a single solution or multiple products are used for disinfecting and storing the lenses (13, 39). Hydrogen peroxide is known to be very effective at contact lens disinfection due to its broad activity against bacteria, fungi, and *Acanthamoeba* species and its ability to destroy these pathogens by oxidation (13). It is active against *Acanthamoeba* cysts when a concentration of

**TABLE 2.** Two contact lens solutions containing hydrogen peroxide tested with *A. castellanii*, *A. polyphaga*, and *A. hatchetti* at 6 h and 24 h of contact

<table>
<thead>
<tr>
<th>Contact lens solution (manufacturer-recommended contact time)</th>
<th>No. (%) of plates positive for the following amoebae at the indicated times:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>A. castellanii</em></td>
</tr>
<tr>
<td></td>
<td>6 h</td>
</tr>
<tr>
<td>AMO UltraCare (6 h)</td>
<td>2/3 (66)</td>
</tr>
<tr>
<td>Ciba Vision Clear Care (6 h)</td>
<td>0/3 (0)</td>
</tr>
</tbody>
</table>

**TABLE 3.** Nine non-hydrogen peroxide-containing contact lens solutions tested with *A. castellanii*, *A. polyphaga*, and *A. hatchetti* at 4 to 6 h and 24 h of incubation

<table>
<thead>
<tr>
<th>Contact lens solution (manufacturer-recommended contact time)</th>
<th>No. (%) of plates positive for the following amoebae at the indicated times:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>A. castellanii</em></td>
</tr>
<tr>
<td></td>
<td>4–6 h</td>
</tr>
<tr>
<td>Alcon Opti-Clean II (4 h)</td>
<td>3/3 (100)</td>
</tr>
<tr>
<td>Alcon Opti-Free Express (6 h)</td>
<td>3/3 (100)</td>
</tr>
<tr>
<td>Alcon Opti-Free Replenish (6 h)</td>
<td>3/3 (100)</td>
</tr>
<tr>
<td>AMO Complete MoisturePlus (4 h)</td>
<td>3/3 (100)</td>
</tr>
<tr>
<td>Bausch &amp; Lomb Boston Simplus (4 h)</td>
<td>3/3 (100)</td>
</tr>
<tr>
<td>Bausch &amp; Lomb ReNu MoistureLoc (4 h)</td>
<td>3/3 (100)</td>
</tr>
<tr>
<td>Bausch &amp; Lomb ReNu Multiplus (4 h)</td>
<td>3/3 (100)</td>
</tr>
<tr>
<td>Ciba Vision AQuify (4 h)</td>
<td>3/3 (100)</td>
</tr>
<tr>
<td>Kirkland Signature Multipurpose Solution (6 h)</td>
<td>3/3 (100)</td>
</tr>
</tbody>
</table>
strains isolated from different geographic areas, possibly be-
tween studies. The reason for the variance in the results between studies was the most resistant strain; it survived in all solutions used five different (1, 3, 5, 11, 12–14, 19, 20, 25, 26, 31, 38, 39). Shoff et al. (39) reported in studies that test contact lens solutions are highly significant and most contact lens wearers do not soak lenses longer than 8 to 12 h (overnight). Current International Organization for Standardization (ISO) and Food and Drug Administration (FDA) regulations do not provide guidelines for testing of the efficacies of contact lens solutions against Acanthamoeba species (3, 16, 30). Without an accepted standard for testing, the procedures used and reported in studies that test contact lens solutions are highly variable. Strains differ and the methods of cultivation and cyst production vary, thus clouding the interpretation of the results (1, 3, 5, 11, 12–14, 19, 20, 25, 26, 31, 38, 39). Shoff et al. (39) used five different Acanthamoeba strains, all of which belonged to genotype T4 but which were isolated from different sources (including AK patients and tap water), and found differential responses among the various isolates to the different contact lens solutions. They found an overall survival of 54.4% for Ciba Vision Clear Care solution and 25.5% survival for AMO UltraCare solution (39). One isolate recovered from Chicago tap water was the most resistant strain; it survived in all solutions tested at 24 h of incubation except the AMO UltraCare solution. The reason for the variance in the results between studies is unclear but might be due to inherent differences that exist in strains isolated from different geographic areas, possibly be-
cause of the development of resistance after exposure to differ-
toxic chemicals in the environment.

In one study by Borazjani and Kilvington (3), existing ISO and FDA guidelines for the testing of the efficacies of contact lens solutions against bacteria and fungi were modified to test for Acanthamoeba species. A 3-log-unit reduction in the number of Acanthamoeba amoebae was required to establish efficacy by the use of these guidelines. Of the four no-rub/rinse solutions tested, Bausch & Lomb ReNu MoistureLoc achieved a ≥3-log-unit reduction in the numbers of trophozoites and cysts of the Acanthamoeba species; the Alcon Opti-Free Express solution was also highly effective and achieved a ≥3-log-unit reduction of trophozoites within 6 h. In another study, it was determined that certain commercial products that contain propylene glycol induce Acanthamoeba encystment (20). However, a reduction or absence of encyst-
ment has been observed with other commercial solutions contain-
ing propylene glycol, suggesting that additional factors, such as buffering systems, may be involved (20).

Testing standards need to be developed to evaluate the efficacies of contact lens solutions against Acanthamoeba cysts. To date different strains and species of Acanthamoeba have been used by various investigators, and this presents several challenges. First, most investigators have used strains that were isolated many years ago and that have thus continuously grown axenically for many years. Hence, these strains are highly selected and may not truly represent the isolates that are currently causing AK in patients. In a recent paper, Köhler et al. (21) demonstrated that Acanthamoeba strains, especially those that have been in axenic cultivation for a number of years, not only lose their ability to encyst synchronously but also experi-
ence a decline in their encystment potential. This is in part because of the downregulation of certain genes that are essen-
tial for the survival of strains under inhospitable conditions. Amoebae grown continuously in axenic medium are provided with abundant nutrition and a constant temperature and, hence, do not need to develop strategies for survival. In con-
trast, newly isolated strains from AK patients have been sub-
jected to inhospitable conditions, including desiccation and con-
tamination with toxic substances in their milieus. Further-
more, it has been shown that continuous cultivation in an axenic medium makes the amoebae lose their virulence (24, 37).

A second challenge is the way in which the amoebae are processed for testing. Most of the researchers have used axenically grown amoebae that have been induced to produce cysts by nutrient deprivation in the presence of Mg²⁺ (11, 27). Encystment in such media may not always produce 100% ma-
ture cysts, which may in turn affect the biocide resistance of the cysts. A mature cyst has two layers in the cyst wall: an outer wrinkled ectocyst that is made of protein and an inner thick, stellate, polygonal, triangular or round endocyst largely con-
sisting of cellulose which is very resistant to physical and chem-
ical agents. Any interference in the maturation process will unduly affect the resistance of the endocyst because resistance to biocides develops during the cellulose synthesis phase of encystment. Previous studies have shown that inadequate aera-
tion and improper control of pH may also hamper encystment (e.g., 8% encystment versus >80% encystment with aeration and no pH control [6, 27]), leading to imperfect cyst wall synthesis. Variation in buffers and the inclusion of a chelating
agent (EDTA) or the use of dimethyl sulfoxide in the test solutions may also adversely affect the efficacies of the biocides (18, 42).

Hughes et al. (14) showed that strain age, the number of passages in axenic culture, and the method of encystment have great influences on the efficacies of therapeutic agents used to kill cysts. Kilvington and Anger (19) also suggested that these differences may be due to the different methods of cyst production, which may explain the discrepancies in the cysticidal efficacies of disinfectants reported by many investigators. Another important factor to consider is the time that the cysts were stored prior to their use in testing.

Because of all these challenges, we elected to use amoebae that were directly isolated from patient specimens and then grown with E. coli. Since encystation in starvation medium does not always produce synchronized cyst formation, we used cysts that were generated by growing the amoebae on agar plates coated with bacteria, a process that occurs in nature (19, 21, 26).

The prevention of future cases of AK will require contact lens solutions that are effective against Acanthamoeba species and continued emphasis on proper lens care hygiene. Educating contact lens wearers about the risk factors for AK, including the improper use of contact lens solutions, is important; but a systematic method for evaluating contact lens solutions will reduce the chance that inefficacious solutions are available. We strongly urge the adoption of standardized procedures for determining the efficacy of contact lens solutions for the disinfection of Acanthamoeba amoebae in order to reduce the incidence of AK associated with the use of inefficacious contact lens solutions. FDA held an initial meeting in June 2008 to address the need for standardizing procedures for improving the testing of the efficacies of contact lens solutions. CLAO J. 34(5):406–410.


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The use of trade names is for identification only and does not imply endorsement by the Public Health Service or the U.S. Department of Health and Human Services.

REFERENCES