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The influence of water content and ionicity on the efficacy of soft contact lens care regimens on *Pseudomonas aeruginosa*

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Background: Contact lens care regimens appear to be prescribed based on familiarity or by matching contact lens brands rather than consideration to efficacy.

Aim: This study compared the effectiveness of multipurpose and peroxide cleaning solutions on low- and high-water content ionic and non-ionic soft contact lenses, in removing *Pseudomonas aeruginosa* (*P. aeruginosa*).

Setting: The laboratory work was conducted by health science students in a graduate level programme in the microbiology laboratory at a university in south-eastern South Africa.

Methods: A quantitative analytical experimental design was used. Four groups (labelled I, II, III and IV) of soft contact lenses, varied ionicity and water content were inoculated with *P. aeruginosa* and then exposed to three solutions containing antimicrobial ingredients, polyaminopropyl biguanide (Dymed), hydrogen peroxide (H_2O_2) and polyquaternium-1 (Polyquad). Each group contained 14 soft contact lenses, with the exception of Group III in which eight lenses were used. Saline served as the control. After 18 h, the remaining colony-forming units were counted using visual inspection as an indicator of efficacy against *P. aeruginosa*.

Results: The solution containing H_2O_2 was found to be the most effective in removing *P. aeruginosa* from all Food and Drug Administration (FDA) groups of contact lenses whilst Dymed was found to be comparatively ineffective for this organism. Water content and ionicity had no effect on the efficacy of the solutions.

Conclusion: Practitioners should consider the efficacy of the active ingredients against microorganisms when dispensing contact lens solutions, particularly for contact lens wearers at risk for *P. aeruginosa* infections.

Keywords: water content; ionicity; contact lens solutions; soft contact lens; Dymed; hydrogen peroxide; Polyquad; *P. aeruginosa*.

Introduction

Soft contact lenses, including hydrogel but more so silicone hydrogel, are increasingly being used for the correction of refractive errors.[1] The effective and safe use of soft contact lenses are dependent on an optimal fit, correct insertion and removal technique, as well as good care and hygiene of the lenses.[2] The care regimen of contact lenses should include a thorough disinfection routine with an appropriate contact lens cleaning solution. The purpose of a contact lens solution is to disinfect, clean and hydrate the contact lens primarily to reduce the microbial load that enters into the eye and ensure safe wear and optimal vision.[3] Generally, contact lens solutions can either be categorised as multipurpose or peroxide disinfecting systems.[3] The mode of action of most multipurpose systems is to disrupt the microbial membranes by negating their selective barrier effect which leads to the death of microbes.[3,4] Hydrogen peroxide (H_2O_2), on the other hand, is a strong oxidising agent which disrupts the metabolism of proteins, lipids and DNA in the microorganism, thereby resulting in cell death.[3,4] Inefficient hygiene and care of contact lenses related to either the cleaning technique or efficacy of the cleaning solution is strongly related to microbial contamination of soft contact lenses which can consequently lead to eye infections often involving the cornea.[5] Infections can include bacterial, fungal or amoebic keratitis that lead to inflammation of the cornea and if not treated promptly may cause impaired vision or even blindness.[6]

Bacterial keratitis is one of the most serious complications of a compromised corneal epithelium particularly in contact lens wearers with *Staphylococci*, *Streptococci* and *Pseudomonas aeruginosa (P. aeruginosa)* often being the associated organisms. *Pseudomonas aeruginosa*, an opportunistic gram negative bacteria, is reported as the most common cause of bacterial keratitis in contact lens wearers[7,8,9,10] as it is able to easily adhere to the surface of contact lenses by means of a biofilm which forms within 24 h.[5,8,11,12] The incidence of microbial keratitis linked to *P. aeruginosa* and contact lens wear has been reported as 13.04 cases per 10 000 individuals a year with the pathogen being identified as the causative agent in 70% of cultured contact lens associated microbial keratitis.[6,8] *Pseudomonas aeruginosa* may also display an innate or acquired resistance to cleaning solutions[13,14] , particularly because of its strong adhesion to lenses linked to its surface hydrophobicity.[15] The higher incidence of keratitis with this pathogen, therefore, has been attributed to its virulent features as well as its resistance in removal from contact lenses.[13,16] This emphasises the need for contact lens disinfection solutions to have superior efficacy against *P. aeruginosa*.

Contact lens solutions are formulated to combat and protect against many pathogens. The effectiveness of the solutions has been found to depend on certain lens properties including water content and ionicity[17,18] which influence bacterial adhesion to lenses.[15] Water content refers to the proportion of water in the contact lens or the percentage of water uptake which is dependent on the chemical structure and formulation of the lens.[17,18] Oxygen permeability is expected to increase with an increase in water content with hydrogels but in the case of silicone hydrogels, this has not always been the case.[19,20] This is important as there is a greater risk of infection and lens contamination when the cornea does not receive the required amount of oxygen resulting in hypoxia. However, when compared to low water content lenses, high water content lens tend to be more prone to deposits and thus microorganism adherence.[18,21] In contrast, Miller and Ahearn[22] reported *P. aeruginosa* to have decreased adherence to high water content lenses.

Ionicity of a soft contact lens refers to the surface charge of the lens,[23] and soft lenses may be classified as either ionic or non-ionic. The ionicity of a soft contact lens can affect how quickly protein deposits are formed on the lenses during wear.[23] Ionic materials have a negatively charged surface and therefore may attract positively charged tear proteins, resulting in increased deposit formation.[18] Non-ionic materials are treated to reduce this negative surface charge and may, therefore, be less prone to attract protein deposits.[23] Gopinathan et al.,[6] however, found that ionicity of a contact lens has little to no effect on the risk of contamination.

Many of the previous studies that assessed the disinfectant capability of contact lens solutions against *P. aeruginosa* did not involve contact lenses[9,24,25,26,27] whilst others that involved contact lenses did not include peroxide solutions.[5] No study was found that investigated the effect of water content and ionicity on the efficacy of a contact lens solution in removing *P. aeruginosa* despite findings of variation in adherence of microbes based on these properties. The findings of this study may assist practitioners in prescribing the most effective contact lens solutions for the patient and thereby reduce the risk of infection specifically related to this specific microbe.

Methods

Study design

The study used an analytical quantitative experimental design and was a collaborative study between optometry and microbiology. Data collection commenced once ethical clearance was obtained from the relevant authorities.

Study population and sampling strategy

Non-random purposive sampling was used to select the cleaning solutions and contact lenses. Three, no-rub, cleaning systems were chosen and included either hydrogen peroxide (H_2O_2), PolyQuad (polyquaternium-1) or Dymed (polyaminopropyl biguanide) as the antimicrobial agent. Saline served as a control. The total number of lenses from each Food and Drug Administration (FDA) group is shown in Table 1.

Study setting and data collection

Pseudomonas aeruginosa from the culture collection at the microbiology laboratory was grown on nutrient agar at 37 °C overnight. Single colony was grown in 200 mL of nutrient broth to the log phase growth (optical density [OD] of 0.5 at 595 nm) and the *P. aeruginosa* concentration was adjusted using a spectrophotometer (Bio-Rad, Hercules, CA) at 595 nm to obtain an OD of 0.1 (1×10^8 colony-forming unit (CFU)/mL). Different types of contact lenses were incubated in separate petri dishes with 15 mL of log phase *P. aeruginosa* culture (1×10^8 CFU/mL) in saline solution for 180 min at 37 °C by shaking.

The lenses were removed and each lens was placed in a well with appropriate contact lens cleaning solution as well as in saline and incubated for ~18 h. Then each lens was removed and placed in a test tube with 2 mL of sterile saline. The test tube was vortexed for 45 s and 200 µL was plated onto a nutrient agar plate. The negative control not exposed to *P. aeruginosa* culture was also plated. The agar plates were then incubated at 37 °C overnight. The following day, the remaining visible colony units were then counted using

TABLE 1: Contact lenses selected for the study, with number of lenses used per Food and Drug Administration group.

FDA group	Water content (%)	Ionicity	Material
I (n = 14)	24 (low)	Non-ionic	Lotrafilcon A
II (n = 14)	62 (high)	Non-ionic	Omafilcon A
III (n = 8)	36 (low)	Ionic	Balafilcon A
IV (n = 14)	55 (high)	Ionic	Methafilcon A

FDA, Food and Drug Administration.

visual inspection and averaged. Analysis of variance (ANOVA) was used to investigate differences between groups at a 95% level of significance.

Ethical considerations

Full ethical clearance was obtained by the Humanities and Social Science Research and Ethics Committee of the University of KwaZulu-Natal (HSS/1120/016U).

Results

In Figures 1, 2 and 3, the *y*-axis upper limit has been set to 50 to allow a better representation of the smaller values of the average number (no.) of CFUs remaining for the solutions, however, the approximate number is shown above each respective column. The solutions are labelled in terms of their active ingredients. Figure 1 shows the average number of CFUs remaining in each FDA group of contact lenses following exposure to each of the three different contact lens solutions and the control (saline).

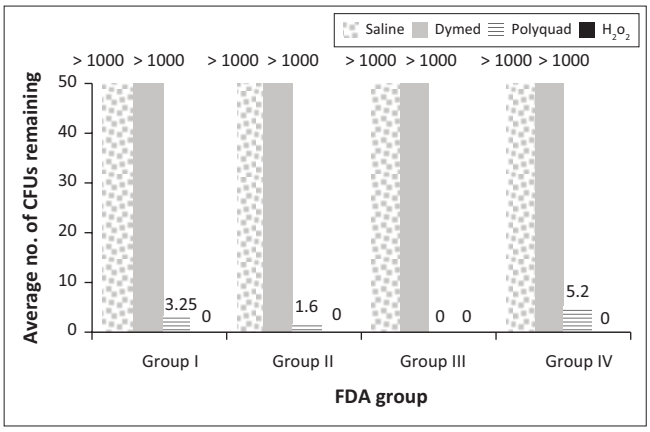
The CFUs remaining in all FDA groups following exposure to both saline and the solution containing Dymed fell in the category 'Too many to count', that is, greater than 1000 CFUs remaining on the lens. Following exposure to the solution containing peroxide (H_20_2), no CFUs remained in any FDA group of lenses. A few CFUs remained in FDA Groups I, II and IV, following exposure to the solution containing Polyquad whilst no CFUs remained on Group III lenses.

Figure 2 illustrates a comparison of the average no. of CFUs remaining on non-ionic and ionic soft contact lenses after exposure to each of the solutions. No significant difference (one-way ANOVA, $p > 0.05$) was found in the average number of CFUs remaining on either non-ionic or ionic lenses after exposure to each of the solutions.

Figure 3 shows the average no. of CFUs remaining on high water content lenses *versus* low water content lenses following exposure to each of the solutions. There appeared to be no significant difference (ANOVA, $p > 0.05$) in the remaining CFUs when comparing high water content to low water content lenses irrespective of the solution used.

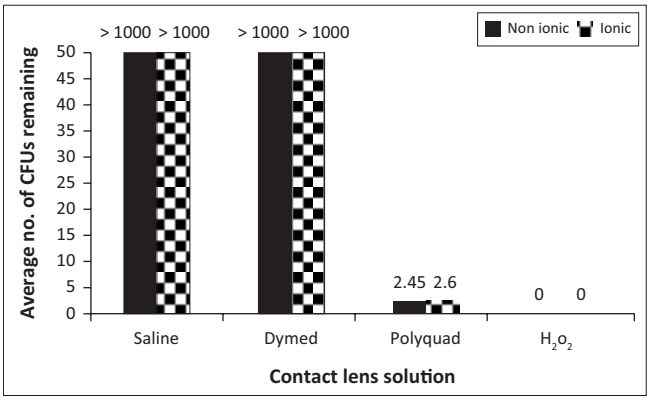
Discussion

Varied efficacy in disinfecting the contact lenses from *P. aeruginosa* was observed with the different solutions analysed. The solution containing H_2O_2 was the most effective as no CFUs of the microorganism concerned remained on the soft contact lenses, irrespective of the FDA grouping, following disinfection. The Polyquad-based solution was the second most effective for all four soft contact lens types whilst the Dymed-based solution appeared to be the least effective against *P. aeruginosa*. These findings may be related to the difference in mechanisms of action of peroxide systems when compared to chemical systems with oxygen releasing solutions and peroxide systems having been reported to be



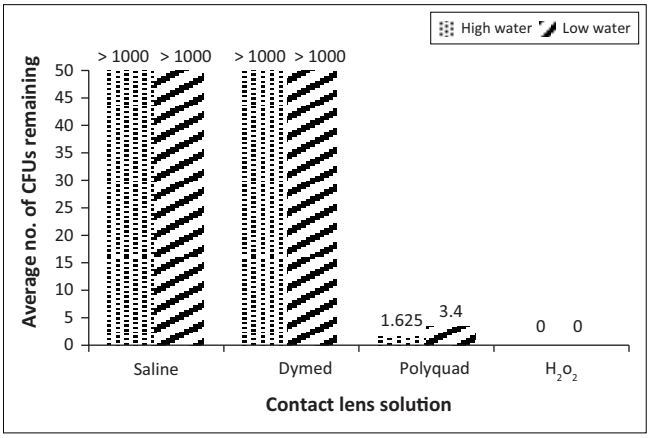
FDA, Food and Drug Administration; CFU, colony forming units.

FIGURE 1: Solution effectiveness on the different Food and Drug Administration groups in removing *Pseudomonas aeruginosa.*



CFU, colony-forming units.

FIGURE 2: Solution effectiveness on non-ionic versus ionic soft contact lenses in removing *Pseudomonas aeruginosa.*



CFU, colony-forming units.

FIGURE 3: Solution effectiveness on high water content versus low water content soft contact lenses in removing *Pseudomonas aeruginosa.*

comparatively more effective against *P. aeruginosa*.[5,14,28,29] Chlorhexidine found in Dymed solutions is reported as being inactive against *P. aeruginosa*[4] and their biofilms[13] which may explain the large number of CFUs remaining on the lenses when treated with this solution. Resistance by microorganisms to frequently used disinfection systems, like chemical regimes, may also be a contributing factor.[7] Furthermore, studies[5,25] have reported poorer disinfection efficacy of solutions

containing Dymed against *P. aeruginosa* when compared to a Polyquad solution consistent with the findings of the current study. In some instances, the Dymed solution did not achieve the required three log reduction.[5] In contrast, an earlier study[26] reported a Dymed solution to be more effective against *P. aeruginosa* than the Polyquad solution tested; however, their study was not performed on contact lenses which were identified as a limitation by the researchers. Of consideration, however, are the findings of Imayasu et al.[30] who reported greater adhesion of *P. aeruginosa* to epithelial cells treated with a solution containing Polyquad compared to the one containing polyhexamethylene biguanide suggesting the possibility of a different *in vivo* result.

Stapleton et al.[31] and Hughes et al.[32] indicated that the higher efficacy of peroxide solutions is expected in the absence of neutralisation, as was the case in this study, which therefore must be interpreted with caution as neutralisation is an essential step when using peroxide disinfection systems. This is particularly so as with the one-step peroxide system, the neutralising platinum disc is introduced during the disinfection process and therefore may not show the same efficacy as found in this study. Moreover, others[3,21,33] have asserted that whilst peroxide solutions may be more effective disinfection solutions, if patients store their lenses for long periods of time then this system may not be ideal as the neutralisation process renders the solution that the lens remains in storage ineffectively as saline which may allow regrowth of microbes. The neutralised solution could not be assessed in this study as it would have meant the use of different vials for the different solutions. Earlier studies which included the neutralising step, however, reported the peroxide solution to still be more effective than other solutions against *Acanthamoeba*[34] and *Acanthamoeba castellanii (A. castellanii)*.[35] The two-step peroxide system is, therefore, hailed to be the solution of choice for disinfection of soft contact lenses and has also been found to be more effective against *Acanthamoeba* than one-step peroxide systems; however, the method is less popular because of the additional step for neutralisation required.[3,21]

This study was conducted on new (unworn) lenses, hence factors like lens deposits and tear components which facilitate the formation of a biofilm and thereby increase bacterial adhesion were not considered in this study.[5]

Efficacy may thus prove differently on used lenses as the ability of the solution to breakdown the biofilm will also be tested, particularly as the biofilm produced by *P. aeruginosa* has been reported to be fairly difficult to remove.[14] However, Dutta et al.[5] revealed, in a systematic review, that *P. aeruginosa* shows greater adhesion to unworn silicone hydrogel lenses compared to *Staphylococcus* microorganisms.

Whilst water content and surface charge are some of the factors reported to influence bacterial adhesion to contact lenses,[15,22,35] the relative efficacy of the solutions against *P. aeruginosa* was not influenced by either water content or ionicity in the current study. Of interest though is the finding by Kierl and Christie [18] that high water content ionic materials undergo changes in lens parameters when soaked overnight in H_2O_2 without neutralisation. Thus, when selecting a contact lens solution, the disinfection ability must also be weighed against toxicity of the solution as compounds from the solution can be transferred to the lens or the eye.

Disinfection efficacy also appears to be organism dependant in that the different disinfection systems have been found to have varied effectiveness on different microorganisms.[5] Whilst the current study revealed the Polyquad disinfection system to be more effective against *P. aeruginosa* than the one containing Dymed, Niszl and Markus[34] and Hume et al.[36] found that solutions with Dymed were more effective against *Acanthamoeba* and *Serratia marcescens (S. marcescens)*, respectively, when compared to Polyquad solutions. Anecdotal reports suggest that the disinfection system chosen by practitioners may be based on familiarity and convenience rather than considering effectiveness of solutions in relation to the risk profile of their patient.

Multipurpose solutions appear to be the preferred contact lens disinfection system[7,14] possibly because of the ease of use, as well as cost whilst peroxide systems are often seen to be inconvenient to use and relatively expensive. Whilst multipurpose solutions may provide disinfection of a broad spectrum of microorganisms,[5] microorganisms are also resistant to the antimicrobial activity of certain contact lens solutions[13] and contact lens practitioners should be considering this when recommending solutions particularly to contact lens wearers who present with recurrent contact lens-related infections.

Even though the current study did not report efficacy of the solutions tested in terms of the International Organization for Standardization (ISO) 14729 standalone test requirements of a 3-log reduction criteria,[5,36] it provided comparative results in terms of the overall ability of the solutions to remove *P. aeruginosa* from a contact lens surface, and provided a relative comparison. Moreover, as there are limited studies that have included peroxide-based solutions, this study adds more information in this area. This study also showed that peroxide solutions do not just reduce the number of CFUs effectively but rather eliminate them completely. It is important that some thought is given to the appropriateness of the chosen contact lens cleaning regime. This study is of particular relevance now and in the near future with the advent of newer medical technological applications of contact lenses such as the delivery of drugs in patients with systemic conditions and smart (digital-integrated) contact lenses being developed for interactions with an evolving digital world which will increase the popularity and usage of such contact lenses.

Conclusion

Solutions containing H_2O_2 and Polyquad appear to be most effective in removing *P. aeruginosa* from hydrogel and silicone hydrogel contact lenses, whilst those containing Dymed appear to be ineffective in removing this microorganism.

Hydrogen peroxide solutions should therefore be considered in contact lens wearers prone to microbial keratitis. The ionicity and water content of a silicone hydrogel lens do not influence the disinfection efficacy of solutions against *P. aeruginosa.*

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Competing interests

The authors declare that they have no financial or personal relationships that may have inappropriately influenced them in writing this article.

Authors' contributions

R.K., S.J., J.H., T.L., S.M., S.N., K.O., M.R. and T.C. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

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Data availability

The data that support the findings of this study are available from the corresponding author, R.H., upon reasonable request.

Disclaimer

The views expressed in the article are those of the authors.

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