Treatment of Ocular Alkali Burns Using Extended Rinsing

BEE 453: Computer Aided Engineering: Application to Biomedical Process

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Table of Contents

Executive Summary:

Many people work every day around potentially hazardous chemicals that can cause severe burns if the worker is exposed to the substance. Ocular alkali exposure is particularly dangerous and without immediate and proper treatment permanent vision loss will occur. The purpose of this project is to assess the pH levels in the eye, after alkali exposure and during subsequent treatments, by accurately modeling the cornea of the eye. We have found using our model that a typical exposure of 1M NaOH for 20 seconds leads to a pH of 14.1 and 12.7 at corneal surface and stroma/aqueous humor interface. After 15 minutes of rinsing with water, our model predicts pH values of 8.2, 11.8, and 12.0 in the corneal surface, stroma/aqueous humor interface, and aqueous humor, respectively. We have also found that it is vitally important to rinse as quickly as possible after exposure, as our model predicts significantly higher pH values and alkali penetration in the eye after only a few seconds of exposure. We have critically evaluated the sensitivity of this model to input parameters and found that it is relatively sensitive to mass transfer coefficient changes, which drastically reduce the minimum pH at the corneal surface. We also have evaluated our model against published literature to demonstrate its ability to model other given situations, specifically using ionic rinsing solutions instead of water. We believe that this model is accurate for modeling the stroma layer, while there is more work to be done in modeling the aqueous humor, which may have an unknown reaction rate for alkali removal. To obtain a better model of this process, we need to learn more about the physiology of the eye. We conclude that it is critically important that an individual try to use external protective equipment, proper training, and proper technique to prevent any exposure and that in the event of an exposure, rinsing begins immediately so that the chemical does not diffuse as far into the eye thus preventing further damage.

Key words: eye, alkali burn, aqueous humor

Introduction:

Thousands of people work every day in environments that contain potentially harmful corrosive chemicals. For the most part, workers safely interact with these chemicals. Occasionally, however, an accident occurs where the worker can be exposed to a particularly corrosive chemical. Most labs that deal with a large amount harmful chemicals have ready access to an eye wash station. The lab users are typically trained to immediately flush their eyes with copious amounts of water immediately upon exposure to a harmful substance.

However, chemical bums also occur in off-duty tasks that do not necessarily involve occupational laboratory work with notably dangerous chemicals. This includes everyday activities such as cleaning, cooking and washing. Alkali bums change the pH from its natural level of approximately 7 to an upper threshold level of 13 which is inherently dangerous. The eye tolerates changes in pH between 5 and 8 without harmful changes occurring (Kompa, et. al 2005). The problem is that the eye has a low buffering capacity and so the addition of a few milliliters of an alkali solution can make a large impact on the pH. Thus an ideal rinsing solution can absorb a significant amount of alkali without changing too much in pH to account for the deficiency in the eye.

Should an alkali bum occur in a real life situation, the first thing that should be done is rinsing using water for 15 minutes as a form of first aid since a specialized solution is unlikely to be readily available. It is essential that this rinsing takes place immediately to reduce the level of alkali penetration in the eye, which can cause permanent damage. Eye rinsing does not always occur and, as a result, the damage is often irreversible.

Objectives:

In this project, we aim to assess chemical flushing from the eye by rinsing with a solution, the most common first aid treatment for alkali burned eyes. To this end, we have developed a model that can estimate the pH level in the various layers of the eye. Our primary goal was to achieve a relatively accurate model that could predict pH changes in the eye over various rinsing times. We want to compare to published literature to see if our model can in fact accurately predict their results. Also, we want to relate rinsing time to pH level trends in order to provide an assessment and estimation of appropriate rinsing times for various exposure levels and times. Finally, we want to investigate the use of solutions besides pure water for rinsing.

We have modeled the diffusion of an alkali chemical into the cornea for various exposure concentrations and times. To follow this, we have also modeled the use of a rinsing solution to remove these chemicals from the eye. From this model, we can calculate the concentration of the alkali in the various layers of the eye, which can be used to determine the pH at those points. In this report, we will present the model and its motivation, our results with a thorough discussion, a qualitative description of our results, in-depth analysis of our model and its use, and our conclusion and future design recommendations to improve our model.

Motivation for model:

We modeled the cornea of the eye by considering it to be a flat cylinder with known layer thicknesses taken from literature (given below). This is possible because we are considering the cornea layer only, which has a relatively shallow radius of curvature that can be approximated as a flat surface. We used a discrete chemical layer to model a set amount of splashed alkali on the eye transiently diffusing through the layers for a given exposure time. From literature, the epithelial layer was known to have been immediately destroyed by alkali contact, and therefore it is not included in this model. We then modeled a constant flow of water over the cornea surface (the stroma in this case) through the use of a mass transfer coefficient at the boundary. The aqueous humor has a removal rate that was also obtained from literature.

Results:

In this section, we will present our assumptions, quantitative pH values obtained from model predictions, and a qualitative analysis of our results.

Assumptions:

(1) The cornea's radius of curvature is small enough compared to its diameter that it can be approximated as a cylinder with known dimensions from literature.
(2) The chemical burn is confined to the area of the cornea.
(3) The initial burn does not penetrate significantly into the aqueous humor (semiinfinite assumption) and therefore any trace alkali concentrations in that layer can be ignored.
(4) The eye is initially at a neutral pH of 7.44, which does not contribute a significant level of alkali concentrations (approximately zero).
(5) The principle form of mass transfer is through diffusive forces and not osmotic ones.
(6) Tissue densities were assumed to remain constant during exposure and rinsing.
(7) The epithelial layer was instantaneously removed upon contact with the alkali.
(8) There is no significant amount of reaction with the introduced alkali due to the high amount that is immediately introduced.

Our results deal with our assumed diffusion of 1 M of alkali through the stroma for an exposure time of 20 seconds. This is assumed to be a plausible situation for chemical use and ability to get to the nearest eye wash station. Most eye wash stations use a constant stream of clean water, so this model is based on that. We rinsed for fifteen minutes, an arbitrary and generally accepted time of rinsing. Then, we calculated the pH in the various layers of the eye.
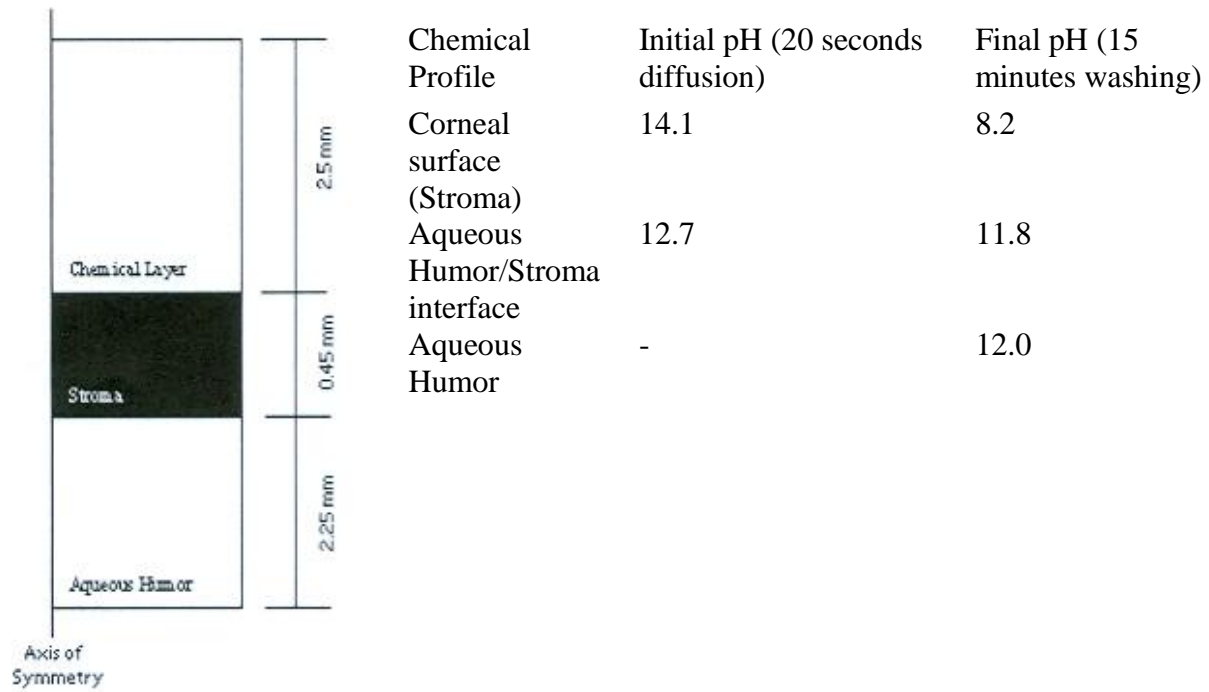
Chemical Profile	Initial pH (20 seconds diffusion)	Final pH (15 minutes washing)
Corneal surface (Stroma)	14.1	8.2
Aqueous Humor/Stroma interface	12.7	11.8
Aqueous Humor	-	12.0

Figure 1. The schematic shows the profile used for the alkali diffusion model in the eye. In the rinsing mechanism, the chemical layer is gone due to the mass transfer coefficient on the top layer of the stroma simulating the effects of irrigation by water

We also wanted to see the importance of immediately rinsing the eye to prevent prolonged exposure. To do this, we took our model and calculated the pH levels after 15 minutes of rinsing with water for exposure times of 1, 5, 10,20, and 38 seconds.
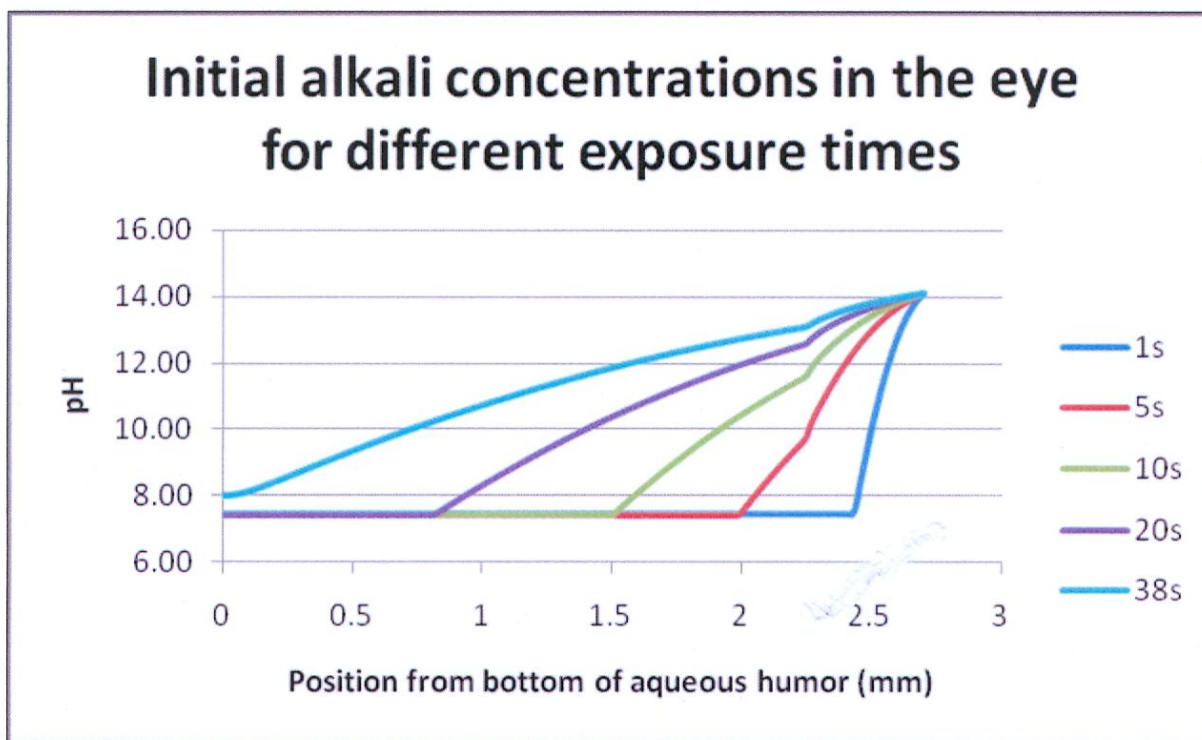

Figure 2. This graph shows the diffusion of the alkali ions into the eye after 20 seconds of exposure to 1 M NaOH. This model shows a linear diffusion through the layer, and as can be seen from the slight pH changes, the alkali does not fully penetrate into the aqueous humor.

Longer exposure times have a drastically greater effect on the pH change throughout the eye. The alkali manages to penetrate all the way through the aqueous humor at 38 seconds, our maximum exposure time. Therefore, it is extremely important to minimize the exposure time as it greatly affects the amount of alkali penetrating through the eye.
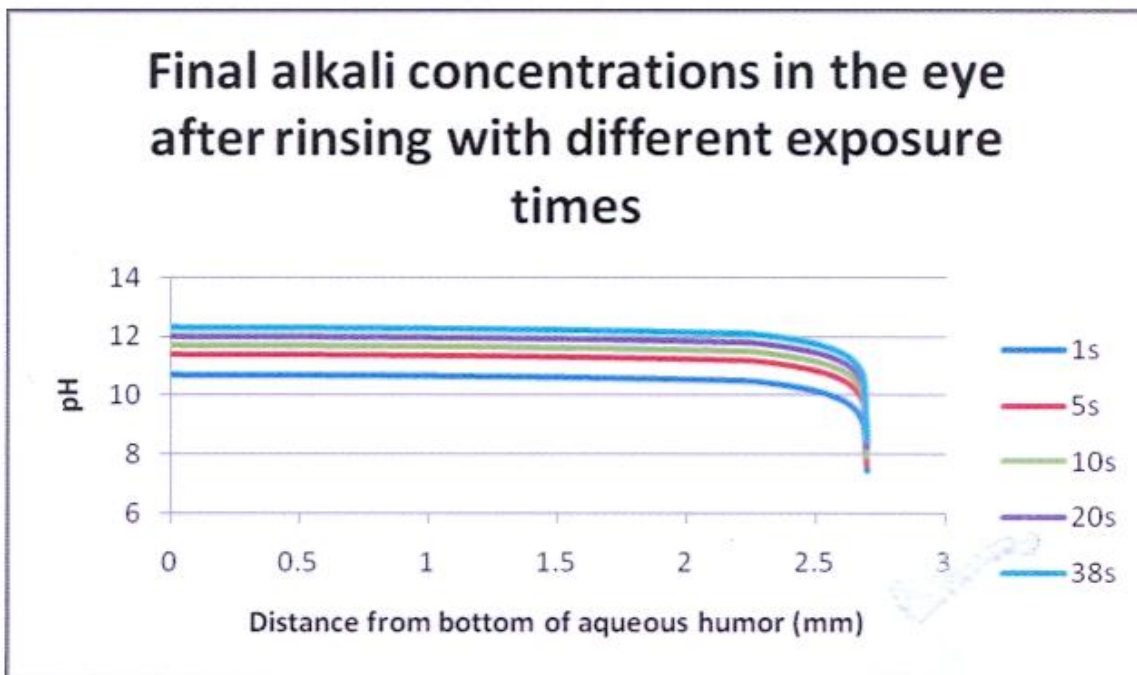
Figure 3. This graph shows the change in pH concentration after 15 minutes of rinsing. Notice in particular, the jump in pH levels between 1 second and 5 seconds followed by gradual increases in pH levels due to increased exposure times, emphasizing the importance of rinsing.

This graph shows the different pH levels after rinsing for 15 minutes with the different exposure times. The minimum exposure has the lowest maximum pH, which hovers at around 10.5 through most of the eye. This is not nearly as damaging as the pH levels obtained by the other exposure times. There is a significant change by 5 seconds, where the maximum pH jumps to around 11.5. At this point, it is still beneficial to begin rinsing, but this benefit quickly drops off as time moves on. By 38 seconds, the pH only changes to about 12.5. Obviously, it is not realistically possible to begin rinsing within 5 seconds of exposure. However, it does underline the importance of how quickly a significantly damaging level of alkali can penetrate the eye.

For our result of 15 minutes of rinsing with a 20 second exposure time, the pH remains steady in the aqueous humor (0-2.25 mm) in the range of 11.5-12.0 and then drastically drops inside the stroma to a pH of 8.2. This is probably because the stroma has a lower diffusivity value, which prevents the accumulated alkali in the aqueous layer from diffusing through. As this figure shows, the pH at the cornea surface drops to somewhat normal levels, though the pH in the lower layers remains at dangerously high levels. This may be due to a flaw in the model used, as discussed in the accuracy section. It makes sense in our model that the pH drops sharply in the stroma layer, as this layer is directly exposed to the water (and therefore the mass transfer coefficient). The further parts of the eye from the rinsing water have to still diffuse through the entire stroma, which explains why they tend to get caught up in the aqueous humor.

This may be caused by a flaw in the flow model in the aqueous humor. The water flow in the aqueous humor may have some sort of turbulent or mixing behavior due to the

constraints of the chamber. This would then contribute to the reduction of the pH in the aqueous layer by natural removal, a key part of returning the pH of the eye to normal. Our model does indeed incorporate a removal rate as a source term, however, this may not be sufficient to accurately model flow behavior in the chamber.

Note: Authors of the scientific papers have been contacted with a query regarding the natural removal method of alkali in the eye.

Sensitivity analysis:

In this section, we will present an analysis that will show the sensitivities of our model to various input parameters. We will look at the input parameters for diffusivity in the alkali and stroma layer, initial alkali exposure concentration, mass transfer coefficient, and aqueous humor removal rate.

1) Alkali layer

When the diffusivity of the alkali layer is altered, so are the pH values obtained. The diffusivity value used for the initial models was 5.273E-9. We tried changing this value up and down an order of magnitude.

Area of eye	Order of magnitude (+/-)	Exposure	Rinsing
Corneal surface	$5.273*10^{-10}$ (-1)	13.9	8.0
Stroma/aqueous humor interface		12.4	11.6
Bottom of aqueous humor		-	11.8
Corneal surface	$5.273*10^{-9}$ (0)	14.1	8.2
Stroma/aqueous humor interface		12.7	11.8
Bottom of aqueous humor		-	12.0
Corneal surface	$5.273*10^{-8}$ (+1)	14.2	8.8
Stroma/aqueous humor interface		12.8	12.4
Bottom of aqueous humor		-	12.6

Table 1. Sensitivity of pH values to diffusivity values in the alkali layer. Notice that the pH values for the corneal surface remains the same but the pH values for the stroma and aqueous humor has a greater rate of change with respect to diffusivity, which makes sense because diffusivity is dependent on distance

Table 1 shows that the pH values tend to decrease as the diffusivity of the alkali layer is lowered during exposure. The pH values for rinsing are also lower as the initial diffusivity of

the alkali layer is lowered. This makes sense since less alkali would be able to initially diffuse and therefore there would also be less to remove during rinsing. It is important to note that an entire order of magnitude change has a relatively small effect on the pH values. For instance, between the orders of 10^{-9} and 10^{-10}, the pH at the surface of the cornea changes only 0.2. With two orders of magnitude change for the surface, the pH changes a mere 0.8 in value. Therefore, this model is relatively independent of small errors or changes in the value of the alkali layer diffusivity.
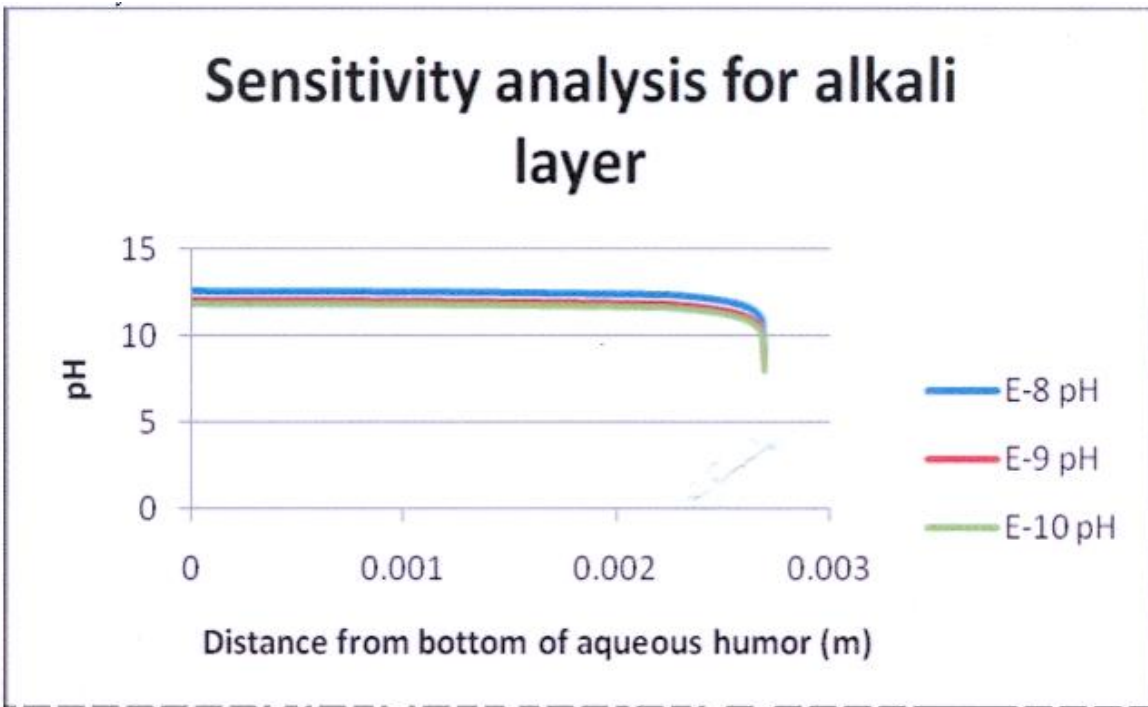

Figure 4. Sensitivity of pH values to diffusivity values in the aqueous humor.

2) Diffusivity of the stroma layer

Area of eye	Order of magnitude (+/-) [m^2/s]	Exposure	Rinsing
Corneal surface	$1.27*10^{-10}$ (-1)	14.2	7.1
Stroma/aqueous humor interface		10.8	11.5
Bottom of aqueous humor		-	11.5
Corneal surface	$1.27*10^{-9}$ (0)	14.1	8.2
Stroma/aqueous humor interface		12.7	11.8
Bottom of aqueous humor		-	12.0
Corneal surface	$1.27*10^{-8}$ (+1)	13.9	8.2
Stroma/aqueous humor interface		13.8	10.8
Bottom of aqueous humor		-	11.7

Table 2. Sensitivity of pH values to diffusivity values in the stroma

The stroma diffusivity value used for the initial model was 1.27E-9 m^2/s. We tried changing this value up and down an order of magnitude. An interesting thing to note is the effect that the diffusivity of this layer has when it becomes higher than the aqueous humor diffusivity. In our actual model, both the diffusivities for the aqueous humor and the stroma are on the same order of magnitude (10^{-9}). When the stroma diffusivity is lowered an order of magnitude, it has the expected effect on the aqueous humor - it lowers the amount of pH since less alkali diffuses in initially. However, when it is higher than the aqueous humor in terms of order of magnitude, it has an unexpected effect. The stroma at a higher diffusivity allows a greater amount of alkali to diffuse into the eye initially. However, since the aqueous humor is at a much lower diffusivity compared to the stroma, it has a certain resistance effect to the alkali, forcing it to accumulate in the stroma. When the rinsing begins, this accumulated alkali quickly diffuses back out of the eye through the stroma, while whatever made it into the aqueous humor slowly diffuses back to the stroma. This creates a pH that would be comparable to other values at the bottom of the aqueous humor. It also creates a pH value that would be drastically lower at the stroma/aqueous humor interface since, as mentioned before, the alkali is quickly diffused back out of the eye into the rinsing solution through the higher-diffusivity stroma.
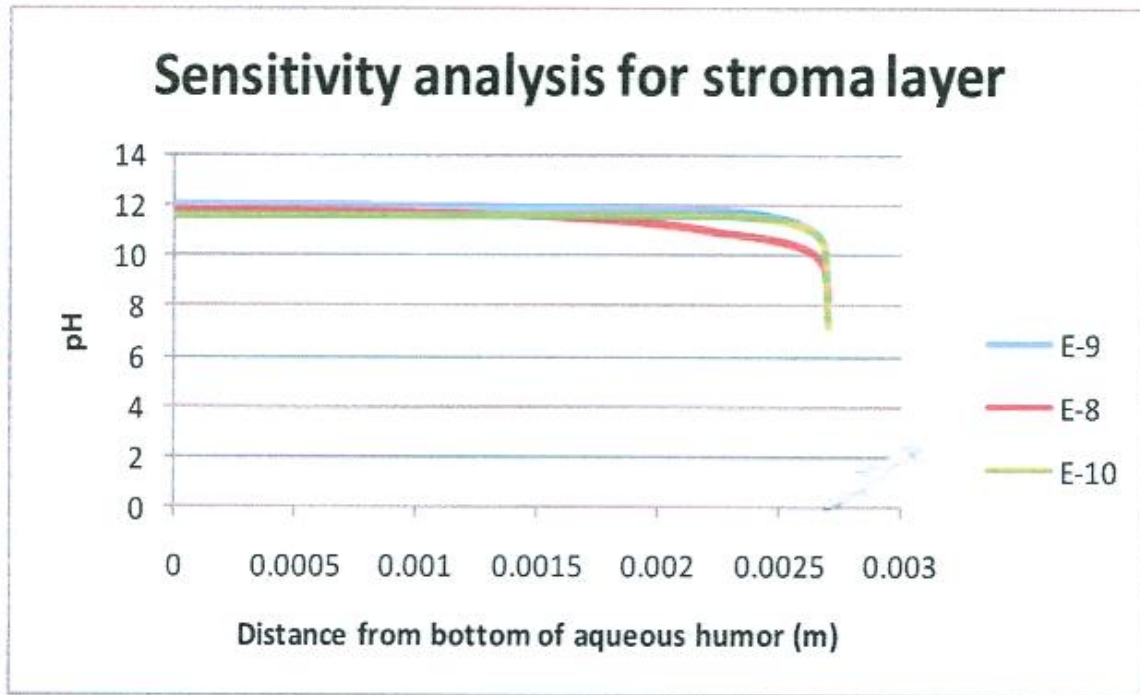
Figure 5. Effect of varying diffusivity values in the stroma on the pH after rinsing.

3) Concentration

Area of eye	Concentration	Exposure	Rinsing
Corneal surface	1000	13.8	8.0
Stroma/aqueous humor interface		12.4	11.6
Bottom of aqueous humor		-	11.7
Corneal surface	2000	14.1	8.2
Stroma/aqueous humor interface		12.7	11.8
Bottom of aqueous humor		-	12.0
Corneal surface	4000	14.4	8.6
Stroma/aqueous humor interface		13.6	12.2
Bottom of aqueous humor		-	12.4

Table 3. Sensitivity of pH values to initial concentration values. Unlike the sensitivity to the change indiffusivity, the concentration change affects the pH values of each layer evenly

We varied the concentration values from 1000 to 4000 to observe the pH changes. From the model, we can see that as the initial concentration increases, the pH and concentration of alkali will also increase. Also, the penetration depth of alkali will be greater with the higher

initial concentration. The pH values are also higher for the rinsing process with the high concentration because there is more alkali left in the eye.
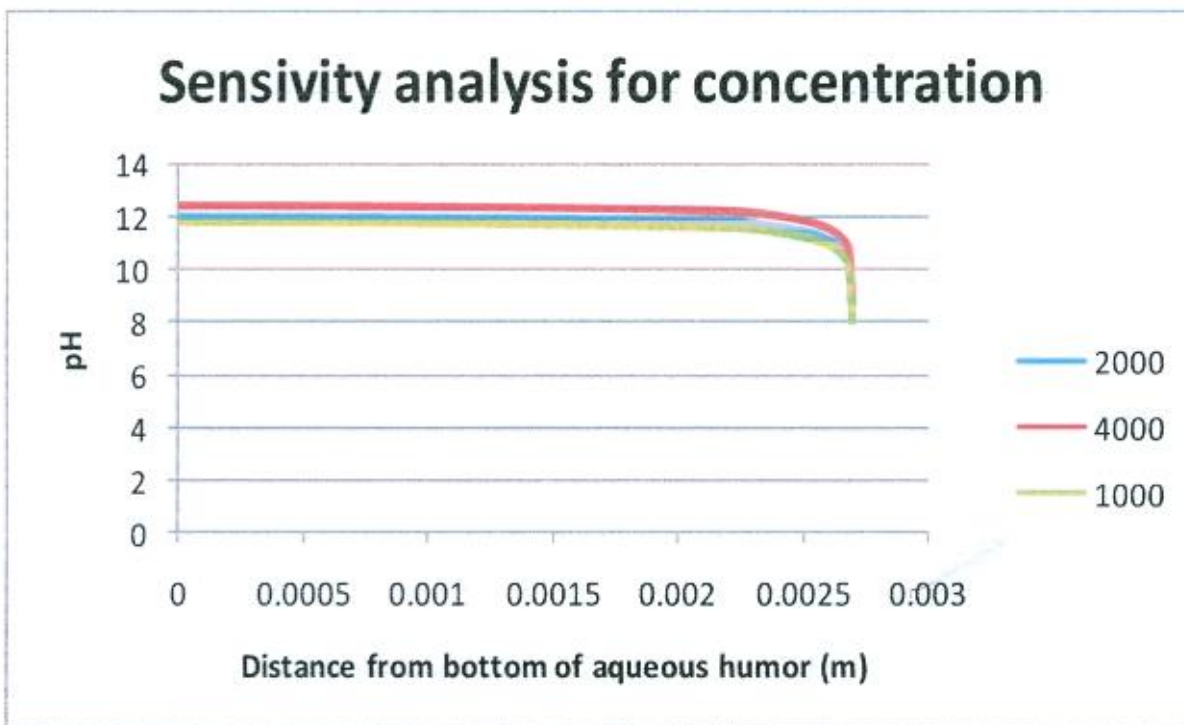

Figure 6. Effect of concentration on the final pH values after rinsing
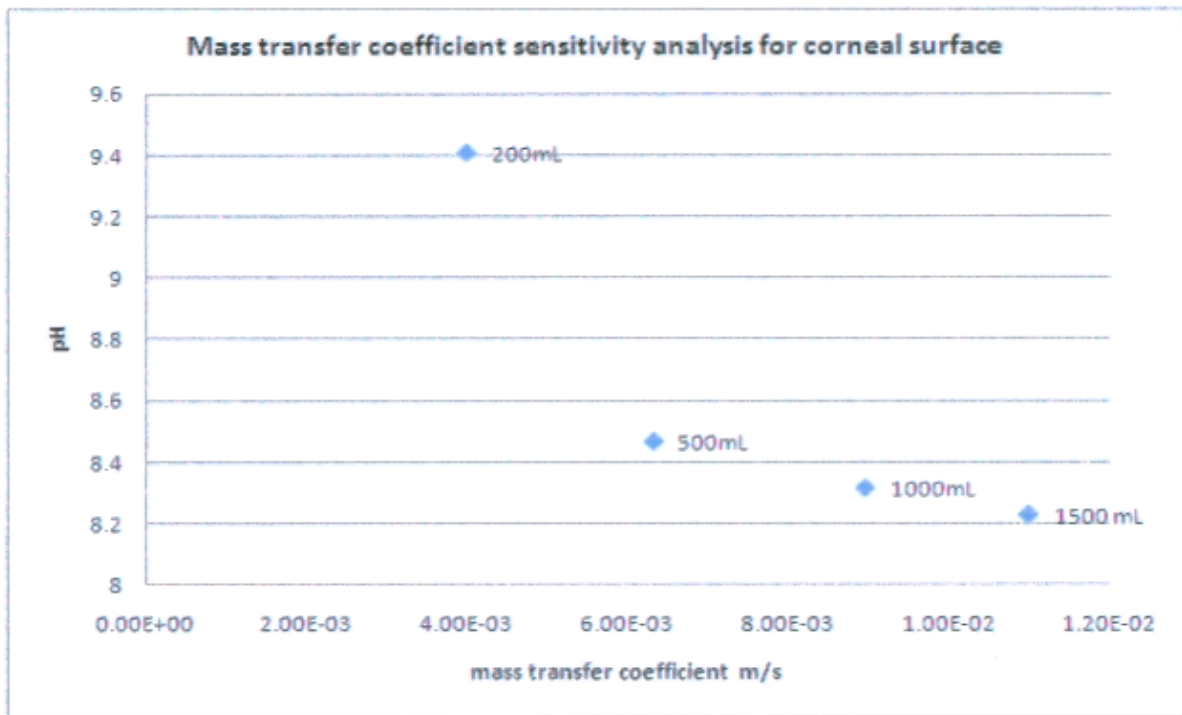
4) Mass transfer coefficient sensitivity

Figure 7. Effect of mass transfer coefficient on corneal surface pH, by changing it $\pm$ 30%

Mass transfer coefficient relates to the volume of water used in this case. Change in flux of water and thus its velocity was assumed to correlate with the volume of water used. Figure 7 shows the effect of using different volumes of water on the corneal surface. Using very minimal amount of water, 200ml, increases the pH significantly in the corneal ~.J1fface but pH value converges to pH around 8.2 as water volume increases to 1500mL.
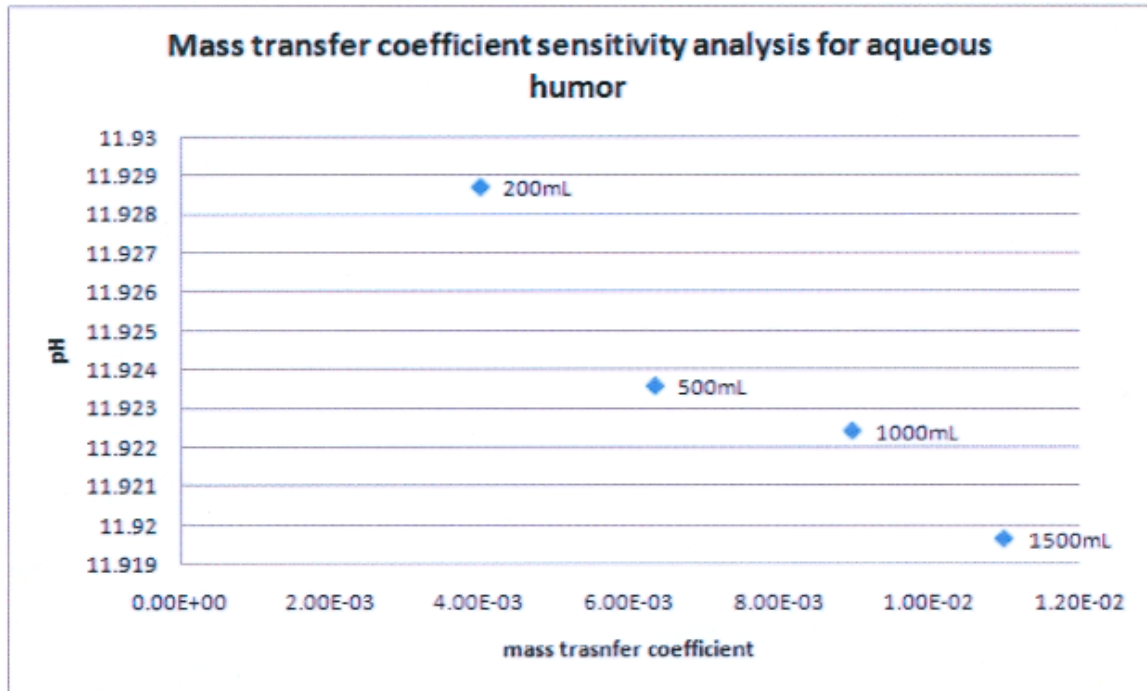
Figure 8. Effect of mass transfer coefficient on Aqueous Humor pH, by changing it ±30%

Figure 8 is a similar plot as figure 7 in the aqueous humor. The pH in the aqueous humor is not as sensitive to the mass transfer coefficient in the corneal surface; the pH change is only 0.01 between the two different volumes of water used. The aqueous humor is deeper in depth from the water irrigation and thus the volume of water and the mass transfer coefficient than in the corneal surface. Although aqueous humor pH is not as sensitive to mass transfer coefficients, since the corneal pH is sensitive, larger volume of water should be used.
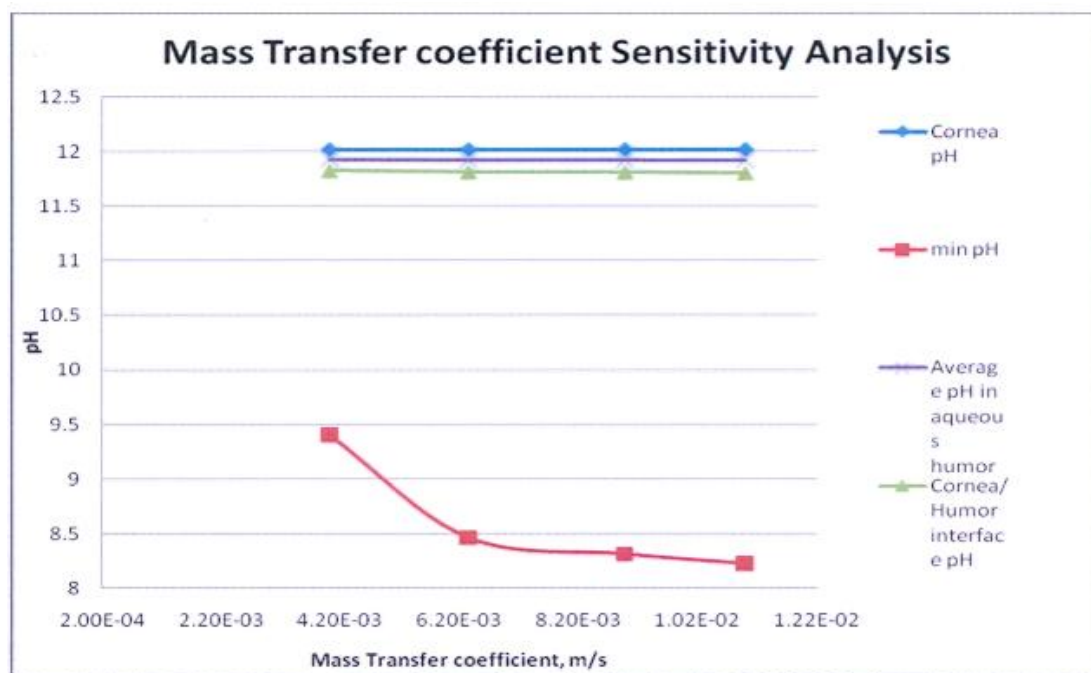
Figure 9. Effect of mass transfer coefficient on pH

Figure 9 summarizes the sensitivity analysis for the four different mass transfer coefficients that depends on different volumes of water used. Far left points indicate the mass transfer coefficient when volume of l500ml of water was used for 920 seconds resulting mass transfer coefficient of 1.10E-02m/s. The middle points are when 1000 of water was flown with mass transfer coefficient of 8.98E-03m1s and the last points are with 500ml of water with transfer coefficient of 6.35E-03 m/s and 200mL of water used with 4.02E-03 m/s.

Mass Transfer Coefficient				
volume, ml	1500	1000	500	200
Um/s	0.163043	0.108696	0.054348	0.021739
hm m/s	1.10E-02	8.98E-03	6.35E-03	4.02E-03
pH,max	12.0122	12.01225	12.01242	12.01275
ph,min	8.2266	8.31471	8.465383	9.40654
ph, middle	11.80188	1.18E+Ol	11.81174	11.82436~
h, average	11.91965	11.92242	11.92357	11.92869
variability				
phMax	0	-0.00035151	-0.0017572	-0.00457
phMin	0	-1.07103529	-2.90257152	-14.343
phMiddle	0	-0.06053077	-0.08350437	-0.19044
hAverage	0	-0.02318306	-0.03282877	-0.07584

Table 4. Effect of mass transfer coefficient on final pH values

Table 4 shows that the variability among the pH due to different mass transfer coefficient is less than 5% except for the minimum pH in the surface of the corneal. We increased/ decreased the volume of water by two folds, thus changing the velocity by two folds. However, this change does not result significant change in the pH levels in the eye. Thus, according to our sensitivity analysis, pH minimum might change according to the different mass transfer coefficients but other variables have almost no significant change in their pH values.

5) Aqueous Humor Removal Rate

Chemical Burn	Chemical Layer (mol/m3)	Stroma (mol/m3)	Aqueous Humor (mol/m^3)	(pH) Chemical Layer	(pH) Stroma	(pH) Aqueous Humor
-2E-1 *c	1291.67	74.81	7.74E-06	14.11	12.87	5.89
-2E-2*c	1323.32	119.99	7.21E-04	14.12	13.08	7.86
-2E-3*c	1338.23	137.24	0.001178	14.13	13.14	8.07
-2E-4*c	1348.43	138.76	0.001239	14.13	13.14	8.09
-2E-5*c	1335.94	138.85	0.001225	14.13	13.14	8.09
-2E-6*c	1338.24	130.25	0.001229	14.13	13.11	8.09

Table 5. Effect of the aqueous humor removal rate on the pH during exposure, there are no significant changes in the Chemical Layer or the Stromal Layer but there are distinct changes in the aqueous humor

Chemical Removal						
Removal Rate (mol/(m3sec))	Chemical Layer (mol/m3)	Stroma (mol/m3)	Aqueous Humor (mol/m^3)	(pH) Chemical Layer	(pH) Stroma	(pH) Aqueous Humor
-2E-1 *c	3.0	33.0	0.00	11.48	12.52	8.07
-2E-2*c	4.1	168.7	1.00	11.61	13.23	11.00
-2E-3*c	4.4	240.5	1.97	11.65	13.38	11.29
-2E-4*c	4.4	249.8	2.11	11.65	13.40	11.32
-2E-5*c	4.4	250.1	2.12	11.65	13.40	11.33
-2E-6*c	4.5	250.6	2.12	11.65	13.40	11.33

Table 6. Effect of the aqueous humor removal rate on the pH during rinsing, again there are no significant changes in the Chemical Layer and the Stromal Layer but distinct changes in the Aqueous Humor

As expected, the addition of the removal rate of alkali in the aqueous humor has the most significant effect in the aqueous humor. When increasing the magnitude of the removal rate by 5 orders, the result is a change in pH of 3 in both simulation models of chemical bum and chemical, removal in the aqueous humor. The top of the epithelium remains relatively unchanged despite the difference in the removal magnitude while the boundary of the aqueous humor and epithelium changes by less than 0.5, under the same conditions. Therefore the addition of the removal rate of alkali is a legitimate addition to our model because it accounts for the, lower pH in the aqueous humor while maintaining the relative pH's of the other two layers.

Accuracy check:

Here, we will compare and discuss our model and its predictions to those of published literature. To do this, we will use their conditions in our model and compare our results with theirs. We will first compare with Spoler, et. al., which was the basis for our alkali penetration model. We will then use two other papers to show how our model predicts pH levels in the two layers of the eye we have modeled.

For our initial condition, we tested our model against two data sets provided by (Spoler et al., 2007). In each case, a total of 500 uL ofNaOH was applied directly to the cornea surface on the eye. The first ocular burn trial in this paper used an exposure of 1 M NaOH, which took about 120 seconds to penetrate the eye. The second trial used 2 M NaOH and only took 38 seconds to penetrate the eye. Our models indicate that the 1M NaOH solution yielded approximately 130 mol/m3 after 120 seconds at the stroma/aqueous humor boundary versus about 170 mol/m3 after 38 seconds for the 2M NaOH application.

Nevertheless, this article does not provide specific concentration or pH values. Instead, it measures how long it took for the alkali to penetrate the cornea. Under this assumption, the values obtained for the bottom boundary of the stroma indicate that our model is an acceptable approximation of these observations. However, our model shows a pH that is slightly higher than 14.0 in the cornea directly after the burn. This is contrary to what we have found where the

pH immediately after burn on the corneal surface is approximately 13.0 (Kuckelkorn, et al., 2001). Despite this, we believe our model is relatively accurate, considering it is an approximation of a real world example. For later calculations, we assumed that the burn exposure is only 20 seconds and then rinsing with water begins flushing out the alkali layer.

To test our removal results, we compared calculated pH values at various layers in our model to empirical data displayed in two articles. Our data does not match the data in these papers, and we likely suspect that this is due to our semi-infinite assumption for the aqueous humor layer. First off, there would be some diffusion of the NaOH to underlying layers in the eye. This would not affect the initial solution, where NaOH does not significantly penetrate to the bottom of the aqueous humor. Rather, it would affect how the NaOH is removed from the eye during irrigation, as shown by the excessive accumulation ofNaOH in the aqueous layer compared to results from the papers. However, our model does show the same trend of pH values over time in comparison to the papers.

First, we compared to Kompa, et al. 2005, using an initial 60 second exposure of 2856 mol/m^3 as described in the paper. We found that our average aqueous humor pH under their testing conditions was about 12.8 after 15 minutes of rinsing. Their paper lists that the maximum pH reached in the aqueous humor should instead be around 10.3. This is quite far off; however, this is where we think a more complicated model would take into account diffusion through other tissues. We recently added a removal rate that helped drop the pH by 0.1 (from a previous value of 12.9 without removal rate accounted for. However, this is clearly still far off from the paper value.

We also compared to Kuckelkorn, et al. 2001. As mentioned, our updated model takes into account a removal rate in the aqueous humor. Even with that, we found that our pH value for corneal surface was 13.9 after burn and 10.0 after rinsing for 5 minutes, which represents no change. This is compared to the value of 13 and 9, respectively, obtained by Kuckelkorn, et al. Their values are less precise than ours, which may actually imply our values are closer to theirs than they seem. Also, they do not specify a volume for NaOH application during the initial burn. Therefore, we used our initial condition approximation of the 2 M alkali burn for 38 seconds previously mentioned to calculate the initial alkali concentration profile in the eye.

We also tried to model an ionic solution on the eye by using a concentration value at the surface instead of a mass transfer coefficient. Our results showed an average aqueous humor pH of 12.9, compared to the expected 9.34 in Kuckelkom, et. al. Again, it appears that our approximation is not very accurate to their results. This is most likely due to some level of reaction in the tissue that needs to be modeled. Still, it should be considered that we used our initial condition approximation since they did not specify it. If we had more details on the initial application volume, our results may have been significantly more accurate.

In conclusion, we think that our results are a fair approximation of the alkali diffusion and removal in the eye. There is more work to be done in creating a more accurate model, however. Despite this, the model we have created gives a good idea on the pH trends within the eye for each event. We are comparing with articles that do not always give the full details necessary for a completely fair comparison. An ideal model would take into account all of the ionic interactions, a 3D model of the eye, and all of the diffusivities in all of the tissues during exposure.

Conclusion and Design Recommendations:

Our results indicate that our model provides an accurate representation of the reaction of the human eye to the foreign presence of alkali. This means that this model, with the addition of several complications and further research can be used as a means of testing for clinical studies.

Chemical eye injuries occur not only at work but also at home from regular household products. The most common alkalis that we encounter at work are the hydroxides of ammonia, sodium hydroxide, and potassium hydroxide. Even at home, we may have substances that contain alkalis like fertilizers and cleaning products. In this project, we are interested in the treatment for alkali bum injuries that is more dangerous than acid eye bums. When alkalis penetrate the surface of the eye, they cause injury to mostly the external surfaces like the cornea and the conjunctiva. The internal surfaces like lens are occasionally affected.

The severity of alkali bums depends on how quickly chemical burned eyes are treated at first. Water is often used to dilute the substance and wash away the particles in the eye. Our model can be used to find out how the pH in the eye is affected by alkali bums with different concentrations and times. Also, we can observe the pH changes for washing with water after the chemical bum.

There is no set amount of washing, but doctors usually recommend one liter of fluid (citation). Depending on the severity of bums, the eye has to be washed until the pH returns to the normal. The rinsing process prevents the chemical breakdown of proteins, and the 20°C cold. solutions delays the chemical reaction in the eye. (Schrage et al) When initial therapy is delayed or missed, other treatment options including surgery are needed.

When the eye's rehabilitation from chemical bums is unlikely, surgery is mainly performed to reconstruct the cornel and conjunctival surface. Recently, transplantation of a limbal stem cell allograft is suggested as a way to reconstruct the cornel surface. The clinical trials have shown that the stem cell survival determines the efficiency of the vision recovery. Glaucoma and retinal detachment are treated by keratoprosthesis, which is a plastic replacement of the central area of an opacified cornea. (Schrage et al).

In other cases, a severe inflammatory reaction occurs from the breakdown products of the eye tissue that act as antigens. This causes the shrinkage of the corneal surface due to the rise of intraocular pressure. The solutions like Acetazolamide or surgical intervention must be applied to block the production of aqueous humor. If a patient shows initial glaucoma, a combined tenonplasty with trabeaulotomy is performed to achieve the normal pressure level.

According to our model, the pH values for the corneal surface do not exactly match with the experimental data. However, the model shows comparable pH changes and concentrations of alkali throughout the eye. The difference between the calculated and experimental data is due to the assumptions and simplifications. The complete solution needs to include a three dimensional model of the eye and all of the chemistry in the eye.

Even though water is the most commonly used as the first-aid treatment for chemical burned eyes, experimental data has shown that Diphoterine is more efficient than water. It takes less time with Diphoterine to reach the optimal pH in the corneal surface. Therefore, we can compare different rinsing fluids like Cederroth Eye Wash Solution, Diphoterine, Ringers lactate solution, and phosphate buffer for the washing process. However, these solutions may not be viable for use as rinsing solutions as they have to be abundantly and easily available. Also, it is difficult to create a model that is accurate to the human eye simply for the reason that

there is no practical way of gathering data by doing the same experiment safely on human eyes. Further studies can be still be performed on pig eyes to determine which solution is more efficient for the treatment of alkali eye burns.

Appendix A:

Schematic:
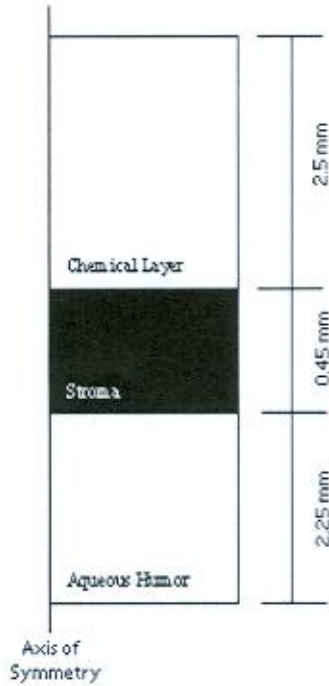
Governing Equation for the Chemical Burn:
1-D cylindrical mass transfer with diffusion and transient terms:

$$\frac{\partial c}{\partial t} = D\left[\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\partial c}{\partial r}\right) + \frac{\partial^2 c}{\partial z^2}\right]$$

Governing Equation for the Chemical Removal by Rinsing:
1-D cylindrical mass transfer with diffusion and transient terms:

$$\frac{\partial c}{\partial t} = D\left[\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{\partial c}{\partial r}\right) + \frac{\partial^2 c}{\partial z^2}\right]$$

Initial Conditions (Chemical Diffusion):

There is an initial concentration of alkali (2000mol/m^3 NaOH) in the alkali layer.

Boundary Conditions (Chemical Diffusion):
The flux at all of the boundaries is zero.

Values:

Mass transfer coefficient: 1.1E-02 m/s (Datta et. al 2008)

Fluid removal rate (turn-over) from aqueous humor: 2.0E-4 s^{-1} (Solomon, et. al 2002)

Diffusivity of stroma layer: 1.27E-9 m^2/s (Spoler,et. al 2007)

Diffusivity of alkali layer: 5.273E-9m^2/s (Samon, et.al 2003)

- Mass transfer coefficient is calculated assuming that water is flowing over a vertical plate using nondimensional numbers.

- $$Sh_L = 0.036 \mathrm{Re}^{4/5} Sc^{1/3}$$
$$Sh_L = 0.664 \mathrm{Re}^{1/2} Sc^{1/3}$$
where $h = \dfrac{Sh_L D}{\mu}$

- Diffusivity values of stroma and alkali layers are given in the articles.   Rinsing of the eyes would most likely be turbulent, but our values change depending on the velocity.

Mass Transfer Coefficient	
u m/s	0.0163
L, m	0.02
r, kg/m^3	997
m,Ns/m^2	0.000959
D	1.45E-07
Re	3390
Sc	6.62
Sh	75.5926
Cross Sectional Area, m^2	0.00001
h_m m/s	1.10E-2

For the case of washing the chemical layer with water for 920 seconds, the velocity was calculated using the following assumptions:

For 920 seconds volume of 1500 ml of water was washed with vertical cross sectional area of 0.00001 m2• The cross sectional area of 0.0001 m2 was used by assuming that the water flow is 1 mm thick with eye width of 1 cm. The diffusivity of the water was assumed to be that of the water in eye. (Datta).

Diffusivity of Alkali in Stroma/Cornea:
The following experimental result of NaOH penetration depth in vivo was used to estimate the diffusivity of NaOH in the cornea.
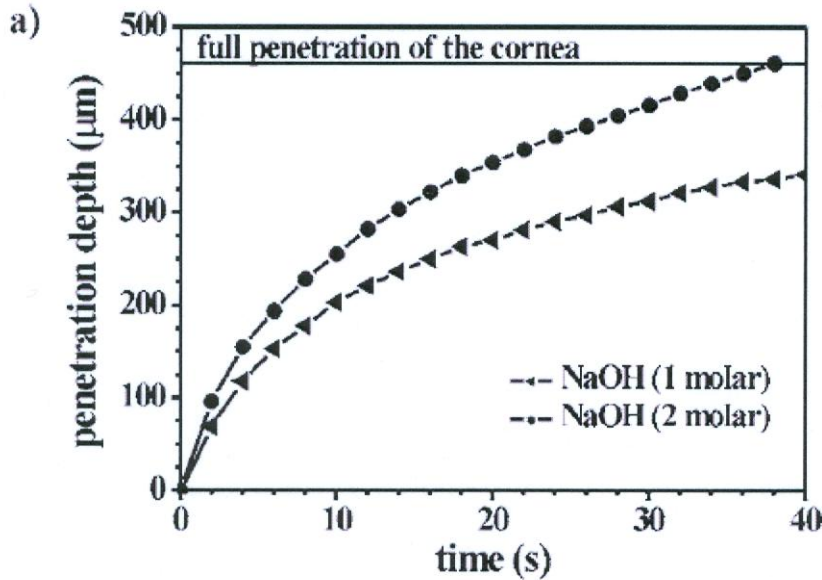

Figure 10. Graph used to calculate the diffusivity of the eye in the alkali layer.

Figure 10 shows the numeric analysis of NaOH penetration time and velocity within rabbit cornea derived from OCT times series. Plot (a) shows penetration depth of NaOH of both 1 molar and 2 molar solution and the 2 molar solution was used to calculate the diffusivity using the following equation:

$$Diffusivity = \frac{x^2}{2t}$$

Where x is the average distance moved by diffusion and t is the time it took. From the graph, 2MNaOH took t=38 seconds with x = 450uM. Thus,

$$Diffusivity = \frac{(450*10^{-6}m)^2}{2*38s} = 5.239 \times 10^{-9} \frac{m^2}{s}$$

Initial Conditions (Chemical Removal):
There is an initial concentration profile of alkali (2000mol/m3 NaOH) from the first part of the project across all of the layers.

Boundary Conditions (Chemical Removal):
The flux at the top of the alkali layer is due to water flow over the eye during rinsing. The other boundaries still have a flux of zero.

Appendix B

All formulations and calculations were done using COMSOL Multiphysics 3.3a. This program solves using a direct linear system solver (UMFPACK).

Time step used: 1 second
Tolerances used: Relative tolerance: 0.01
                        Absolute tolerance: 0.0010

Mesh used: We used mapped mesh parameters with a rectangular element. We used an axial element of 2 because we assumed most of the diffusion was 1 dimensional along the z-axis. The number of elements used was 800 in the alkali layer, 200 in the stromal layer, and 1,000 in the aqueous humor layer.

Figure 11. A plot of the structures mesh.

Mesh Convergence:

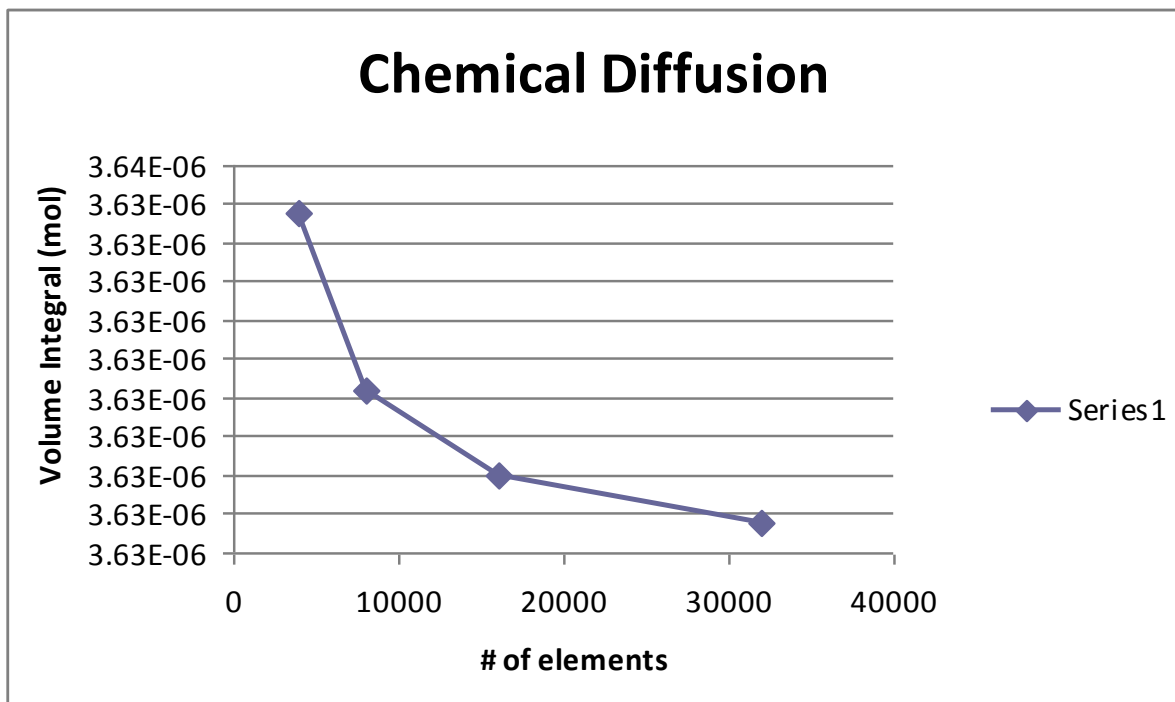|	Chemical Diffusion	
# of elements	Volume integral (mol)	Line integral (mol/m^2)
4000	3.63E-06	3.21404
8000	3.63E-06	3.21402
16000	3.63E-06	3.21401
32000	3.63E-06	3.214005

Table 7. Mesh convergence of chemical diffusion, doubling the number of elements per iteration

Figure 12. Mesh convergence of chemical diffusion doubling the number of elements per iteration
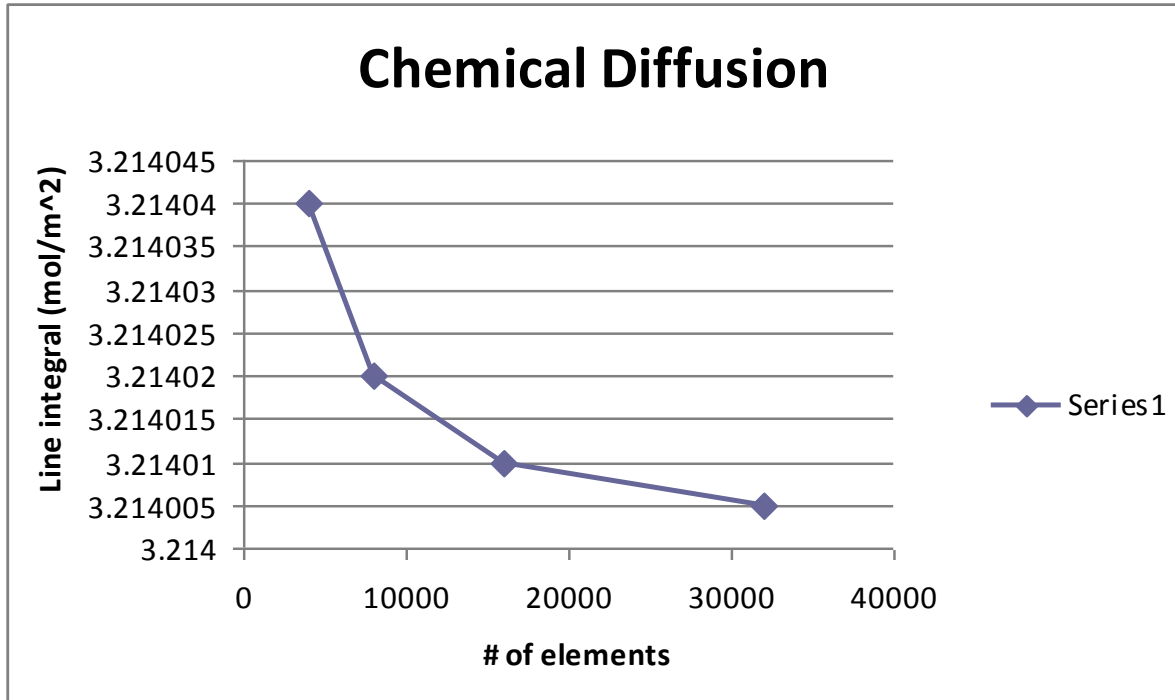
Figure 13. Mesh convergence of chemical diffusion doubling the number of elements per iteration

While the solution in Figure 13 is not fully converged, it is acceptable since it is consistently accurate due to 3 decimal places. Further iterations compute values in the 5th decimal places, due to the limitation of COMSOL solver program and the computer hardware.

| # of elements | Chemical Removal | |
	Volume integral (mol)	Line integral (mol/m^2)
100	1.01E-06	0.895852
500	1.01E-06	0.895854
1000	1.01E-06	0.895854
2000	1.01E-06	0.895854
4000	1.01E-06	0.895854
8000	1.01E-06	0.895854

Table 8. Mesh convergence of chemical removal, doubling the number of elements per iteration
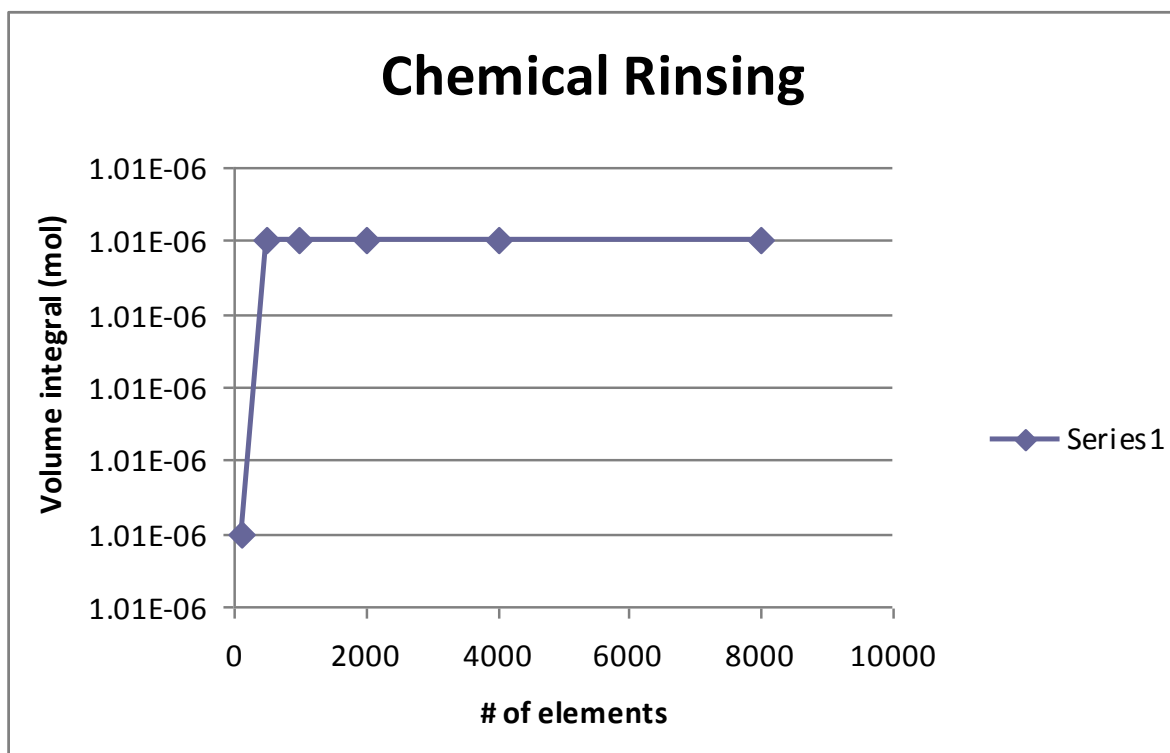
Figure 14. Mesh convergence of chemical removal doubling the number of elements per iteration
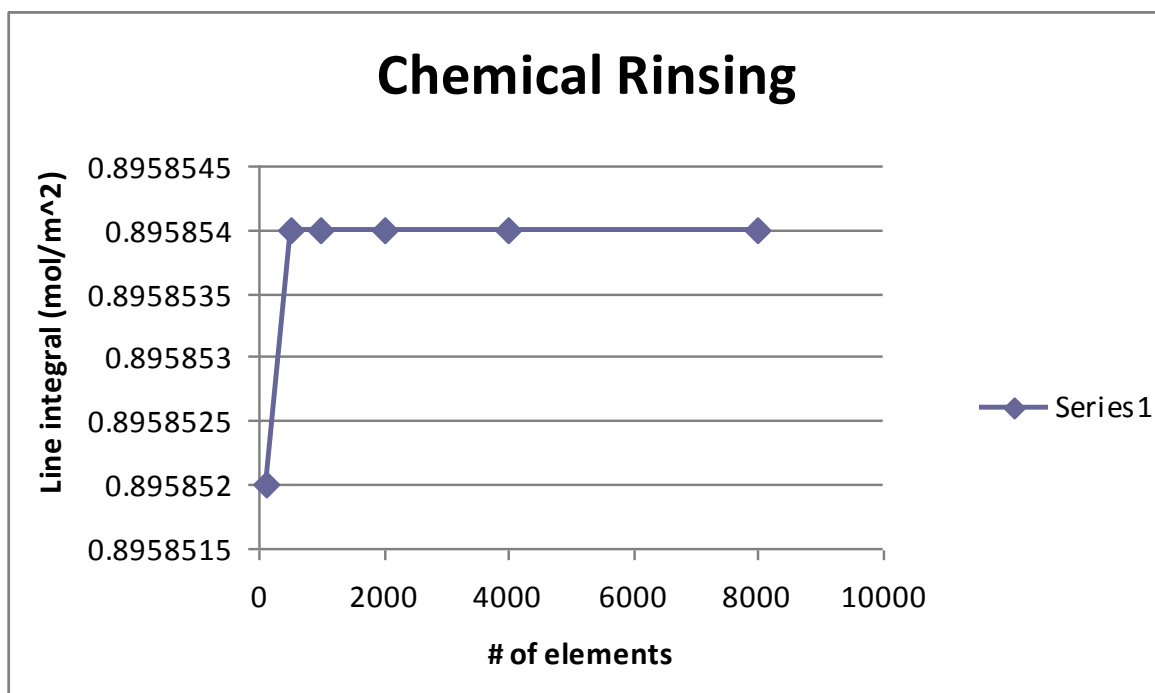

Figure 15. Mesh convergence of chemical removal doubling the number of elements per iteration

Appendix C

Citations:

Datta, A.K. and V. Rakesh. 2008. *An Introduction to Computer-Aided Modeling of Biomedical Transport Processes.*

E. Samson and 1. Marchand. April 2003. *Calculation of ionic diffusion coefficients on the migration of test results.* Materials and Structures, Volume 3, No. 257,156-265.

Kompa, Sirpa; Redbrake, Claudia. 2005. *Effect of different irrigating solutions on aqueous humour pH changes, intraocular pressure and histological findings after induced alkali burns.* Acta Ophthalmologica Scandinavica vol 83: 467--470.

Norbert Franz Schrage, Sirpa Kompa, Wolfram Haller, Stephanie Langefeld. 2002. *Use of an amphoteric lavage solution for emergency treatment of eye burns.* Burns, 28 (2002) 782-786.

Samon, E. Marchand, K.A. Snyder. 2003. *Calculation of ionic diffusion coefficient on the basis of migration test results.* Materials and Strucutres, Vol. 36 156 - 165.

Solomon, Seth, M.D. 2002. *Aqueous Humor Dynamics.* The New York Eye and Ear Infirmary Online. From http://www.nyee.edu/pdf/solomonaqhumor.pdf. Accessed April 17th *2008.*

Spoler, Felix. 2007. *Dynamic analysis of chemical eye burns using high-resolution optical coherence tomography.* Journal of Biomedical Optics, Volume 12, Issue 4,041203.