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Full Length Research Paper

The study of lysozyme adsorption onto 2-hydroxyethyl methacrylate (HEMA) and silicon hydrogel contact lenses

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In order to increase the water content and the oxygen permeability of hydrogels used in the manufacture of contact lenses, the polar monomer, silicon hydrogel contact lenses (SHCL) and 2-hydroxyethyl methacrylate (HEMA) were copolymerized with the hydrogels. Due to the presence of polar monomers in the conventional contact lenses, the major component of the human tear, lysozyme, is extensively adsorbed onto their surfaces. The adsorption of lysozyme onto the contact lens' surface leads to limitations in its application. The present study measured the concentration of lysozyme adsorbed onto the surface of HEMA and SHCL hydrogels by ultraviolet/visible (UV-VIS) spectroscopy. The lysozyme employed was obtained from solutions similar to the concentration of artificial tear. The adsorption results were examined by the Langmuir adsorption isotherm and the constants of this isotherm were also evaluated.

Key words: Langmuir isotherm, protein adsorption, 2-hydroxyethyl methacrylate, silicon hydrogel contact lenses, contact lenses, hydrogels.

INTRODUCTION

Although, the principles involved in the formation of hydrogel polymers have not come to light in the recent years, it has only been since the late 1970s that their potentials have begun to be realized. There is no precise and limiting definition of the term hydrogel, and problems always arise when attempts are made to apply such definitions to the range of materials that are encompassed by the term. Possibly, the most entailing description that could be formulated is that, hydrogels are water-swollen polymer networks of either natural or synthetic origin. With this definition in mind, it is the cross-linked, covalently bonded, synthetic hydrogels whose biomedical application has grown, most dramatically, in recent years. It must be noted, however, that composite structures involving both natural and synthetic hydrophilic materials have also begun to be exploited. In biomedical applications, 2-hydroxyethyl methacrylate (HEMA), offers the greatest advantage over most other hydrophilic gels commonly encountered in biomedical applications with regard to stability to various parameters, for example, pH and temperature. When the polymer is prepared in the absence of water, it is glassy and similar in many ways to poly methyl methacrylates. The amount of water absorbed by this polymer is expressed as the equilibrium water content (EWC) (Liu et al., 2009):

EWC = (weight of water in the gel)/(total weight of hydrated gel) × 100%

The EWC is the most significant single property of the gel, since it is the water held within the polymer substrate that gives hydrogels their unique properties. Thus, the permeability of the membranes, their mechanical properties, their surface properties and the resultant behavior at biological interfaces are all a direct consequence of the amount and nature of water held in this way (Wiliams, 1990).

The cross-linked HEMA are more commonly referred to as poly HEMAs. Hydrogels have been extensively

Table 1. Contact lenses properties.

Commercial name	Manufacturer	Material	FDA group	Water content (%)
Acuvue	Johnson & Johnson Vision Care	Etafilcon A	IV	58
Acuvue and AdvanceTM	Johnson & Johnson Vision Care	Galyfilcon	I	47
Purevision	Bausch & Lomb, Inc.	Balafilcon A	III	36
Focus1 Night & Day	CIBA Vision	Lotrafilcon A	I	24
O2Optix	CIBA Vision	Lotrafilcon B	I	33

studied in the biomedical and pharmaceutical fields for a variety of applications including soft contact lenses (Castillo, 1986) and drug delivery devices (Brazel et al., 1999). Adsorption of proteins to hydrogel surfaces has been the subject of considerable investigation due to the fact that the presence of a protein film can in some cases modify the biocompatibility of the hydrogel surfaces. The amount of protein adsorbed increases with the anionic character of the hydrogels (Robitaille et al., 2010). Despite the heterogeneity of the film, studies indicate that lysozyme is usually the most prevalent protein absorbed by ionic hydrogel contact lenses, due to its low molecular weight and the fact that it is positively charged at physiological pH, while ionic lenses are usually negatively charged. Furthermore, lysozyme is the most abundant protein in human tears constituting one third of the total protein content followed by lactoferrin and tears specific pre albumin (Sassi et al., 1996). Although, many studies have been done on contact lens soiling, one central difficulty is the quantification of deposits as a response variable to different experimental methods. Some of the techniques used for the quantification of proteins include infrared (IR) spectrometry (Mansch et al., 1996), ultraviolet/visible (UV-VIS) spectrometry (Jones et al., 1997), atomic force microscopy (AFM) and X-ray photoelectron spectroscopy (XPS) (Coen et al., 2010; Galli et al., 2009).

Silicon hydrogel contact lenses (SHCL) are the latest kind of soft lenses commercially available. This type of lens provides excellent oxygen transmissibility to the cornea on account of silicone's high oxygen transmissibility when compared with the conventional hydrogel SHCL (Mansch et al., 1996; Crittenden et al., 1998). Silicone is a hydrophobic polymer, and for this reason most of the silicone-based SHCL possesses surface treatment, which decreases the surface hydrophobicity. Reduction in hydrophobicity gives a greater comfort to the wearer and additionally prevents the formation of deposits such as lipids and proteins, as well as microbial colonisation (Lyklema, 1991). Reduction in the lens surface hydrophobicity can be obtained through two methods. The first one consists of performing a treatment on the lens surface, which can be achieved in a gas plasma reactive chamber by creating an ultra-thin permanent coating in the cases of Lotrafilcon A and Lotrafilcon B (Ciba Vision), or by plasma oxidation, transforming the silicone into silicate compounds, in the case of Balafilcon A (Bausch & Lomb, Inc.) (Table 1). The second method consists of the incorporation of a wetting agent such as polyvinyl pyrrolidone (PVP) into the lens surface, which is the case of Galyfilcon A (Table 1) (Johnson & Johnson Vision Care). SHCL, despite the advantages they offer due to their high oxygen transmissibility, they also present some pitfalls, which are related to the migration of the silicone hydrophobic moieties to the lens surface (Lan et al., 2009). As mentioned earlier, less hydrophobic surfaces are advantageous, since they prevent protein adsorption and microbial colonization.

In the present study, UV spectroscopy was used to determine the amount of protein adsorbed onto the surface of the two types of contact lenses, HEMA and SHCL. The results were examined by Langmuir adsorption isotherm and constants of this isotherm were evaluated.

THEORY

Langmuir isotherm

Many different isotherm models have been proposed for the adsorption of solutes from a liquid solution onto a solid surface. Most of these models are essentially empirical, although, theoretical derivations have been accomplished in some cases. Among all models, the Langmuir model is probably the most popular due to its simplicity and its agreement with experimental data. The Langmuir model is expressed by (Crittenden et al., 1998):

$$q = \frac{q_m K_d C}{1 + CK_d} \quad (1)$$

where q (mg/g) and c (mg/ml) are the equilibrium concentration of protein in solute in solid adsorbent and liquid bulk phases, respectively. Constant q_m (mg protein adsorbed/g adsorbent) and K_d (mg protein adsorbed/ml volume of protein solution) are Langmuir parameters. The constant q_m represents the maximum binding capacity and K_d is the dissociation coefficient of the solute-adsorbent complex, which represents the affinity between

the solute and the adsorbent.

The Langmuir isotherm for the adsorption of solute from liquid solution was first expanded directly from the corresponding isotherm of gas-solid adsorption and was later derived thermodynamically, kinetically and stoichiometrically. All these derivations are based on a few common assumptions, namely:

1. All binding sites are equivalent, distinguishable and independent.
2. Each binding site combines with only one solute molecule.
3. A molecule adsorbed onto one binding site does not influence the adsorption of another molecule on a neighboring site (Lyklema, 1991).

The Langmuir isotherm has been widely accepted as a practical method for integrating experimental data of protein adsorption onto hydrogels surfaces (Lan et al., 2009). It is therefore more favourable to obtain the dissociation coefficient and maximum protein binding capacity by rearranging Equation 1. This gives a linear equation as follows:

$$\frac{C}{q} = \frac{K_d}{q_m} + \frac{1}{q_m}C \qquad (2)$$

Graph of *C/q* versus *C* gives a line of an intercept of K_d/q_m and a slope of $1/q_m$.

Measurement of adsorption isotherms is an important first step in the characterization of the interaction between protein and adsorbent. The values of q_m give an indication of the maximum possible capacity of the adsorbents, although, it must be remembered that these maximum values will not be achieved under most operating conditions. The values of K_d give some indication as to what concentrations of adsorbate are needed to achieve capacities approaching the maximum values, q_m. If the adsorption stage is carried out with protein concentration of the same order, as the value of K_d or smaller, only a fraction of the maximum capacity of the adsorbent will be utilized. Only if the concentration of protein is far greater than the value of K_d, will the adsorbent show a capacity approaching q_m and even this capacity will occur only in circumstances where the protein and adsorbent have been contacted for a sufficient period for equilibrium to be reached (Lan et al., 2009).

Excess Gibbs surface

The extent of adsorption related to the adsorption free energy ΔG_{ads} by Oberholzer et al. (1999) is given as:

$$C_s = C_b \int_0^\infty (e^{-\Delta G_{ads}/kT} - 1)\, dz \qquad (3)$$

$$C_s = C_b \int_0^\infty (e^{-\Delta G_{ads}/kT} - 1) dz \qquad (3)$$

where C_s and C_b are the solute concentration on the surface and in the bulk, respectively, and *Z* is the solute-surface distance. The amount of ΔG_{ads} depends on the solute configuration on the surface. The primary contribution to ΔG_{ads} is, of course, from solute-surface interactions, but the effect of interactions among adsorbed solute particles is an essential feature that must also be included.

The lateral interactions of primary interest are the electrostatic interactions. These interactions are computed within the framework of the linearized Poisson-Boltzmann equation (Oberholzer et al., 1999). In the present approach, the interactions are treated as pair wise additive, and this assumption allows ΔG_{ads} to be decomposed into solute-surface (ΔG_{I}) and solute-solute (ΔG_{II}) contributions, namely:

$$\Delta G_{ads} = \Delta G_{\mathrm{I}} + \Delta G_{\mathrm{II}} \qquad (4)$$

Further simplification results from additional approximations that arise from the fact that, ΔG_{ads} is typically several *kT* in magnitude for solute close to the surface and decays with increasing *Z* consequently. The integral in Equation 3 is dominated by the solute particles closest to the surface, specifically, a monolayer of particles differing little in their positions relative to the surface, *Z*. Thus, (ΔG_{II}) can be assumed to be independent of *Z*, and a function only of the configuration of particles in the plane of the adsorbent surface. Thus, Equation 3 may be approximated as:

$$C_s = C_b \int_0^z (e^{-\Delta G_{\mathrm{I}}/kT}) dz = C_b K \qquad (5)$$

where

$$K = e^{-\Delta G_{\mathrm{I}}/kT} \qquad (6)$$

The Henry's law constant *K* has the units of length.

The concentration of solute adsorbed on the adsorbed surface (mg/cm^2) can be expressed as:

$$C_s = \frac{N_s (M_M / N_0)}{A} \qquad (7)$$

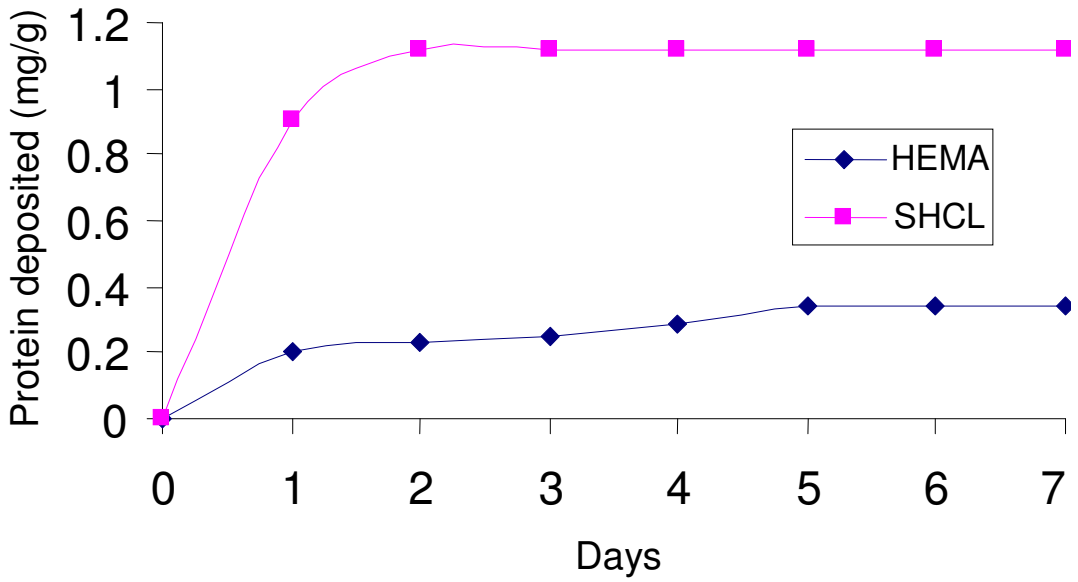

Figure 1. The effect of protein concentration on adsorption on SHCL and HEMA surfaces, protein concentration is 1.2 mg/ml, pH 7.2, 22°C.

where N_s are the number of solute particle adsorbed on surface area (A), M_w and N_0 are respectively, the molecular weight and Avogadro number. The area per solute particle adsorbed on surface is expressed as: $\sigma = \frac{A}{N_s}$. Then, the fractional coverage of the surface is $\theta = \frac{\sigma_0}{\sigma}$, where σ_0 is the actual coverage area by a solute particle. For a spherical particle of diameter d, $\sigma_0 = \pi d^2$, then Equation 7 can be written as:

$$C_s = \frac{\theta M_w}{\pi d^2 N_0} \quad (8)$$

The molar mass of lysozyme is 14600 g/mole and diameter d for the globular protein, lysozyme at pH = 7.2 is d = 1.2 nm (Voet et al., 1999).

MATERIALS AND METHODS

HEMA and SHCL were prepared from Bausch & Lomb, Inc. Company. Monobasic sodium phosphate and dibasic sodium phosphate were prepared for buffer solutions (Merck Company). Hen white egg lysozyme (cat#107255) with purity >99% and Roche molecular were prepared from Biochemicals Company. The concentration of the adsorbed lysozyme was measured through UV spectroscopy from a calibration curve made for lysozyme solution of known concentrations at a wavelength of 280 nm (Sariri, 1997). All buffers were freshly prepared for the experiment. HEMA and SHCL were used as contact lenses as adsorbents (Kimsw, 1987; Peppas, 1987; Ricardo, 1994). The solutions were prepared with similar constituents as the human tear (Cooper, 1982). The lysozyme aqueous solution with the following concentrations of 0.8, 1, 1.2 and 1.4 mg/ml, were prepared using double distilled and deionized (Milli-Q treated) water. The concentration of NaCl was in the range of 0.05 to 0.2 M (Tighe et al., 1993). The contact lenses were placed in phosphate buffer solution, pH = 7.2 (Bruno et al., 1989) similar to that of the tears (Philips et al., 1989). The lenses were placed in the solution and kept for five days at a temperature of 22 ± 0.1°C, to allow the protein adsorption onto the lenses to be completed and to reach the equilibrium state. Samples of solution were taken and the absorbance was measured at 280 nm (M350 Double Beam UV spectroscopy). The concentrations of the adsorbed lysozyme onto the contact lenses were determined through a calibration curve for the known lysozyme concentrations in the solution (Sariri et al., 2005).

RESULTS AND DISCUSSION

Various factors, such as, protein concentration, pH, ionic strength and temperature affect the quantity and quality of protein adsorption. The amounts of lysozyme adsorbed onto SHCL and HEMA contact lenses were also measured and are as shown in Figure 1. The temperature was set at 22 ± 0·1°C, lysozyme concentration is 1.2 mg/ml and the pH of the experiments at 7.2, similar to that of human tears. Lysozyme was chosen as protein in the study. This protein has isoelectric point pH 11, thus, this protein has positive charge at pH experiment (Lehninger, 1982).

Figure 2 demonstrates the effect of the ionic strength of the solutions on lysozyme adsorption. In these experiments, NaCl (0.05 to 0.2 M), the major electrolyte in the human tears, was added to the protein solutions

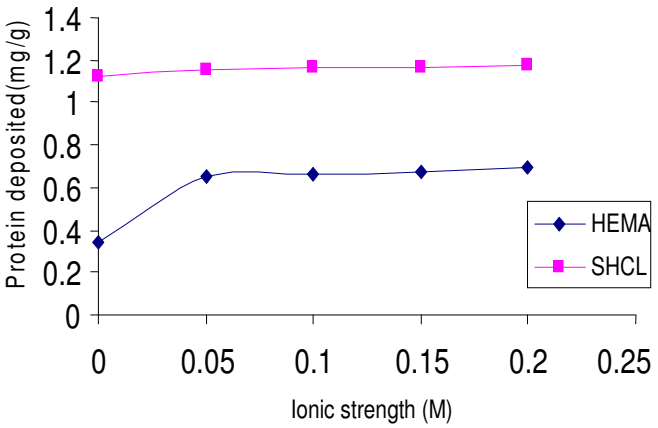

Figure 2. The effect ionic strength of solutions on SHCL and HEMA surfaces, at pH 7.2 and 22℃ concentration of protein is 1.2 mg/ml.

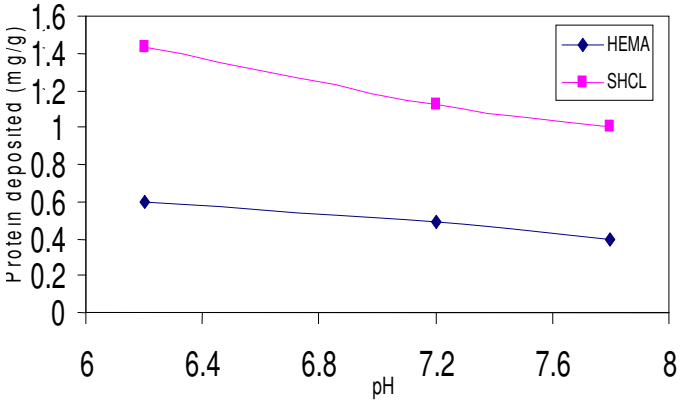

Figure 3. The effect of pH on HEMA and SHCL surfaces, at pH 7.2 and 22℃, concentration of protein is 1.2 mg/ml.

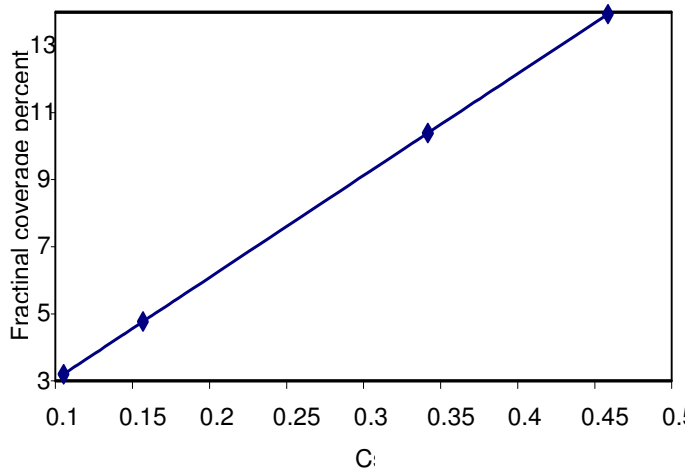

Figure 4. The fractional coverage surface HEMA versus concentration of protein on the surface at pH 7.2 and 22℃.

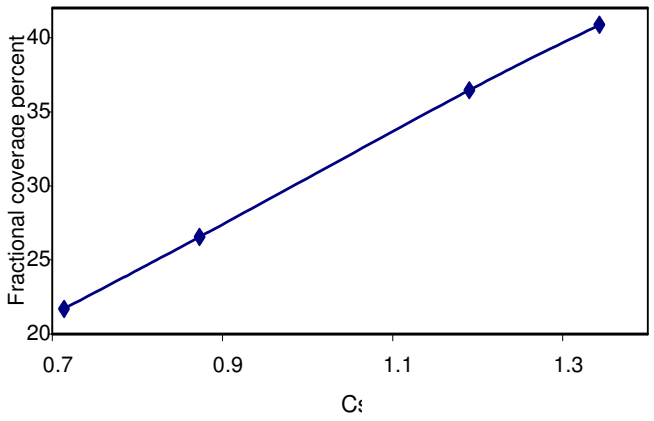

Figure 5. The fractional coverage surface SHCL versus concentration of protein on the surface at pH 7.2 and 22℃.

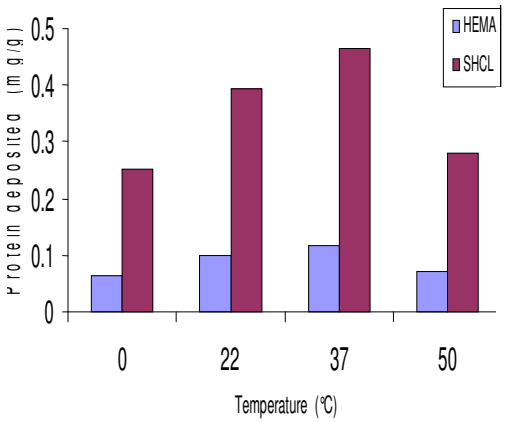

Figure 6. The effect of temperature (ºC) on protein adsorption on SHCL and HEMA surfaces, concentration of protein is 0.8 mg/ml at pH 7.2.

(lysozyme concentration 1.2 mg/ml). Figure 3 illustrates the pH effect on the adsorption of lysozyme on the surfaces of AA and HEMA. Figures 4 and 5 show the fractional coverage of SHCL and HEMA surfaces, based on Equation 8, versus protein concentration at pH 7.2 and 22 ± 0·1℃. Figure 6 shows the effect of temperature on protein adsorption onto SHCL and HEMA surfaces for a 0.8 mg/ml lysozyme concentration. Table 2 reports the values for Langmuir parameters for SHCL and HEMA surfaces.

In order to obtain Langmuir parameters, we need a different concentration of protein. We made lysozyme with concentration of 0.8, 1, 1.2 and 1.4 mg/ml in phosphate buffer at pH 7.2 and 22 ± 0.1℃, and then, the amount of lysozyme adsorbed is measured. Then, with plot *C/q* versus *C,* we can obtain Langmuir parameters. In Figure 1, the adsorption is rapid, initially, and then gradually levels off with longer contact times until it

Table 2. The Langmuir parameters for HEMA and SHCL surfaces at 22°C, pH 7.2.

Sample	q_m (mg/g)	K_d (mg/ml)
HEMA	0.1289	1.7944
SHCL	7.6162	9.3427

reaches equilibrium state. Approximately, 85% of the adsorbed mass is reached within 1 day for both surfaces. As indicated in Figure 1, the concentration of lysozyme on SHCL and HEMA surfaces is at its highest on the fifth day. The results also indicate that the lysozyme is adsorbed to a greater degree onto the SHCL surfaces. In a previous paper, Bos et al. (1994) also obtained strong adsorption of positively charge lysozyme on a positively charged surface. Using a semiconducting tin oxide layer as substrate and varying surface charge by varying the applied interfacial potential. It was found out that at pH 9.9, that is, below the isoelectric point of lysozyme, more protein was adsorbed as the surface was rendered more positively charged. The results on lysozyme adsorption obtained by Bos et al. (1994) are consequently in accordance with the results of this paper. A positively charged protein, even a hard one, can adsorb in high amounts onto negatively charged SHCL surface, as shown in our work by lysozyme at pH 7.2. Between days 0 and 1, the increase adsorbed lysozyme on SHCL rapidly than HEMA surface. Then, between days 1 and 5, the amount of lysozyme increase is adsorbed on HEMA slowly, but for lysozyme adsorbed on SHCL, the amount of protein reaches equilibrium and the increased time is constant. Between 5 to 7 days, the amount of lysozyme adsorbed on both surfaces is constant. The results on adsorption are obtained in accordance with the results of this paper (Sariri et al., 1996). This anomalous adsorption behavior has been observed before (Ramsden, 1992). The reason for this can be explained in terms of the negative surface charge of SHCL, due to the presence of a carboxylate group and positive lysozyme charge at pH 7.2 (Norde et al., 1978). The HEMA surface, on the other hand, has no charge, thereby, less affinity for protein adsorption (Garrett et al., 1998) also observed this behavior (Calonder, 2001). They adsorbed cytochrome C from a solution onto $Si(Ti)O_2$ surfaces.

Figure 2 shows the effect of the solution's ionic strength on the amount of adsorption of protein onto SHCL and HEMA surfaces. The influence of ionic strength on the adsorption has been studied by determining protein adsorbed on SHCL and HEMA surfaces at four concentrations of NaCl, 0.05, 0.1, 0.15 and 0.2 M. The amount of lysozyme adsorbed (increased concentration of NaCl), would lead to a lower affinity between the lysozyme and both surfaces at pH 7.2. This can best be tested at low surface coverage, where the shape of the figure is essentially determined by the lysozyme-surface interaction. The electrolyte concentration primarily exerts its influence on protein adsorption in a different way, for example, by affecting the conformational stability of the protein and/or being adsorbed simultaneously (Norde et al., 1978). We are not able to draw conclusions about the influence of concentration of NaCl, on the interaction between the lysozyme and SHCL surface (Retailleau, 1997). As can be seen upon an increase in the concentration of the protein, the adsorption increases, a phenomenon attributed to the favorable orientation of protein molecules in the presence of sodium ion which causes more protein attraction per surface area of both SHCL and HEMA (Voet et al., 1999; Burns et al., 1996). However, the electrolyte concentration does not have a significant effect on the amount of protein adsorption; this is probably due to the competitive adsorption of lysozyme and NaCl on the hydrogel surfaces.

Figure 3 shows the effect of pH on lysozyme adsorption onto SHCL and HEMA surfaces. The effect of solution pH on protein adsorption appears to be clear and depends on the physicochemical properties of a protein, that is, size, dimensions and electrostatic charge (Hook et al., 1998). The maximum lysozyme adsorption occurred at pH 6.2 and the lysozyme adsorbed at pH 7.8 was minimally onto both surfaces. Lysozyme has positive charge at pH 6.2 and is an isoelectric point of pH 11.1 (Lehninger, 1982). Hence, the charge of lysozyme is positive throughout the pH range used in this investigation. In comparison with SHCL and HEMA surfaces, it is readily anticipated that the strongest electrostatic interaction may occur around pH 6.2 for SHCL. But at this pH (6.2), the surface charge of HEMA is neutral and the amount of lysozyme adsorbed in this surface is less than SHCL surface. With increase in pH protein solution (to 7.8), lysozyme has positive charge, but the magnitude of the positive charge is much than that observed for pH 6.2. At this pH (7.8), the amount of lysozyme adsorbed is reduced for both surfaces. An increase in pH causes a decrease in the adsorption rate. Also, as expected, the amount of adsorption is observed to decrease with increasing pH protein solution. The reason for which can be explained in terms of the lysozyme reduced surface charge as the pH of the protein solution increases. Figure 3 also illustrates the greater adsorption onto SHCL surfaces as opposed to the HEMA surfaces. This behavior was also observed for lysozyme onto octacalcium phosphate crystal film (Roscoe et al., 1993).

Figures 4 and 5 show the fractional coverage of surface versus concentration of protein on the surfaces. These figures show that as the protein concentration increases, so does the surface coverage (note the different scales at the axis). According to the random sequential adsorption (RSA) model (Schaaf, 1989), there is a maximum surface coverage beyond which further adsorption becomes impossible (54.7% coverage for spherical particles). RSA has been successfully used to explain and understand

lots of the experimental result (Ramsden, 1993). In concordance with the previously published results (Ravichandran et al., 2009). At low coverage of both surfaces, the shape of the isotherm is essentially determined by the protein-surface interaction. At high coverage, lateral interactions between adsorbed protein molecules may also play a role in the adsorption process (Ravichandran et al., 2009).

Figure 6 shows the effect of temperature on the lysozyme adsorption. An increase in temperature, to some extent (37°C), increases lysozyme adsorption rate on both surfaces, but at higher temperatures where denaturation of the protein occurs and the amount of protein adsorption is reduced. However, the highest adsorption is at 37 ± 0.1°C, which is the human body's physiologic temperature. This behavior was also observed by Roscoe et al. (1993).

The values of Langmuir parameters (K_d and q_m) shown in Table 2, for SHCL surfaces are higher than those of HEMA surfaces. This indicates the higher dissociation coefficient of the protein-surface and the maximum protein binding capacity of the SHCL surface. The higher value of q_m on SHCL surfaces as compared to HEMA is indicative of the higher amount of adsorbed protein on SHCL surfaces. Also, the higher K_d value for SHCL surfaces as compared to HEMA leads us to believe that there exists strong binding between lysozyme and the surface of the SHCL contact lenses. The main reason for this can be attributed to the presence of positive charges on lysozyme protein (under experimental pH) and negative charge of the SHCL contact lens surface. In concordance with the previously published results (Song, 2000; Lee et al., 2009; Yoon et al., 1999; Martinez et al., 2008; Ijome, 2006), similar findings were noted, however, in the case of non-ionic HEMA and lysozyme.

Conclusion

UV-Vis spectroscopy was used to determine the amount of lysozyme adsorbed onto SHCL and HEMA hydrogel surfaces. The effect of temperature, pH, ionic strength and concentration of protein on the rate of adsorption were examined. Lysozyme adsorbed higher on SHCL surface than HEMA surface at all pH experimental. Lysozyme on the other hand, has its isoelectric point at pH 11.1 and is thus strongly positively charged at pH 7.2. Also, the AA surface carries a negative charge at this pH. Thus, positively charge lysozyme is adsorbed in higher amounts on SHCL surface. This anomalous adsorption behavior has been observed before. But, lysozyme adsorption less on HEMA surface, because this surface is non ionic compound. Based on the study's findings, through an increase in the concentration of the lysozyme protein, the amount of adsorption onto HEMA and SHCL surfaces increases at constant temperature and pH. As for the effect of pH, it can be said, that as a result of an increase in pH, the amounts of protein adsorption will decrease on the HEMA and SHCL surfaces. This finding leads researchers to believe that through the preparation of contact lens washing solutions with a low pH, less than that of tears, one can decrease the amount of protein adsorption. As for the effect of ionic strength, with an increase in the ionic strength of protein solutions, the amount of protein adsorption will be increased. However, the amount of lysozyme adsorption is not influenced as a result of an increase in the solution's electrolyte concentration. The Langmuir adsorption isotherm was applied and the constants of this isotherm were evaluated. The K_d and q_m values for lysozyme protein and SHCL surfaces were higher than those for the HEMA surfaces, due to the presence of a positive charge on the lysozyme protein and a negative charge on the SHCL surface. The results of adsorption were discussed in terms of the protein and hydrogel surface properties.

NOMENCLATURE

A: Surface area (cm^2)
C: Equilibrium concentration of solute in liquid (mg/ml)
C_b: Solute concentration in the bulk (mg/ml)
C_s: Solute concentration on the surface (mg/cm^2)
d: Diameter (nm)
K: Henry's law constant (unit of length)
k: Boltzmann constant
K_d: Dissociation coefficient of the solute-adsorbent (mg/ml)
M_w: Molecular weight (gr/mol)
N_s: Number of solute particle adsorbed
N_0: Avogadro number
q: Equilibrium concentration of solute in solid (mg/g)
q_m: Maximum binding capacity (mg/g)
T: Absolute temperature (Kelvin)
Z: solute-surface distance (nm)
ΔG_{ads} : Adsorption free energy (erg)
ΔG_{I} : Adsorption free energy for solute-surface (erg)
ΔG_{II} : Adsorption free energy for solute-solute (erg)
σ : Area per solute particle adsorbed (cm^2/mol)
σ_0 : Actual coverage area (cm^2/mol)
θ : Fractional of coverage

REFERENCES

Bos MA, Shervani Z, Anusiem AC, Giesbers M, Norde W (1994). Influence of electric potential of the interface on the adsorption of proteins. J. Colloids and Surfaces B: Biointerfaces.3: 91-100.

Brazel CS, Peppas NA (1999). Mechanisms of solute and drug transport in relaxing, swellable, hydrophilic glassy polymers. J. Polymer., 40: 3383-3398.

Bruno TJ, Svoronos PD N(1989). CRC Hand book of basic tables for

chemical analysis. J.CRC Precc, Inc. Provide page number
Burns NL, Brink C(1996). Influence of surface charge on protein adsorption at an amphoteric surface: Effect of varying acid to base ratio. J. Colloid and Interface Sci., 178: 16-122.
Calonder C, Van Tassel PR (2001). History dependence of protein adsorption kinetics. USA .J.Pro. Natl. Acad. Sci., 80(19): 10664-10669.
Castillo EJ, Koenig JL, Anderson JM(1986). Protein Adsorption on Hydrogels. J. Biomater., 6: 338-345.
Coen MC, Lehmann R, Groning P, Bielmann M, Galli C, Schlapbach L (2010). Adsorption and bioactivity of protein A on silicon surfaces studied by AFM and XPS. J. Colloid Interface Sci., 23: 180-189.
Cooper TA, Cooper SL, Peppas NA (1982).Biomaterials:Interfacial phenomena and application.Washington. J. Am. Chem. Soc.199: 233-244.
Crittenden B, Thomas WJ (1998). Adsorption Technology and Design. J. Butterworth-Heineman. Provide page number
Galli C, Coen MC, Hauert R, Schlapbach L (2009).Protein adsorption on topographically nanostructured titanium. J. Surface Sci., 474: 180-184.
Garrett Q, Chatelier RC, Griesser HJ, Milthorpe BK (1998).Effects of charge groups on the adsorption and penetration of proteins onto and into carboxymethylated poly (HEMA) hydrogels. J. Biomater., 19: 2175-2186.
Hook F, Rodahi M, Kasemo B, Brzezinski P(1998).Structural changes in hemoglobin during adsorption to solid surfaces: Effects of pH, ionic strength and ligand binding. J. Biophysical. 95: 12271-12276.
Jones LL, Evans K, Sariri R, Tighe B (1997).Lipid and protein deposition of N-Vinyl Pyrrolidone containing group II and gorup IV frequent replacement contact lenses. J.CLAO. 23(2): 122-126.
Kimsw MEJ (1987).Hydrogels in medicine and pharmacy. J.CRC Press, Inc I. Provide page number
Lan Q, Bassi AS, Zhu J, Margaritis A (2009). A modified Langmuir model for the prediction of the effects of ionic strength on the equilibrium characteristics of protein adsorption onto ion exchange/ affinity adsorbents. J. Chemical Eng., 81: 179-186.
Lee WK, Seungko J, Mankim H (2009).Effect of electrostatic interaction on the adsorption of globular proteins on octacalcium phosphate crystal film. J. Colloid and Interface Sci., 46: 70-77.
Lehninger AL (1982).Principles of biochemistry Worth Publisher. Provide page number
Liu Q, Hedberg EL, Liu Z, Bahulekar R, Meszlenyi RK, Mikos AG (2009). Preparation of macroporous poly (2-hydroxyethyl methacrylate) hydrogels by enhanced phase separation. J. Biomater., 21: 2163-2169.
Lyklema J (1991).Fundamentals of interface and colloid science. Academic Press Limited. Vol. I. Provide page number
Mansch HH, Chapman D (1996). Infrared Spectroscopy of Biomolecules. Wiley & Liss, Inc. Provide page number
Martinez F, Martin A, Pradanos P, Calvo JI, Palacio L, Hernandez A (2008).Protein adsorption and deposition onto microfiltration membrane: The role of solute solute-solid interactions. J. Colloid and Interface Sci. 221: 254-261.
Meijome GL, Alemany LA, Almeida JB, Parafita MA, Refojo MF (2006). Microscopic observation of unworn siloxane-hydrogel soft contact lenses by atomic force microscopy. J. Appl. Biomater., 76B: 412-418. Not cited in the work
Norde W, Lyklema J(1978).The adsorption of human plasma albumin and bovine pancreas ribonuclease at negatively charged polystyrene surfaces. J. Colloid and Interface Sci., 66(2): 257-265.
Oberholzer MR, Lenhoff AM (1999).Protein adsorption isotherms through colloidal energetic. J. Langmuir.15: 3905-3914.
Peppas NA (1987). Hydrogels in medicine and pharmacy. J. CRC Press, Inc. Vol.II Provide page number
Philips AJ, Stone J (1989). Contact Lens. 3 Edition, Butter Worth and Coc publisher. Provide page number
Ramsden JJ (1992). Observation of Anomalous Diffusion of Proteins Near Surfaces. J. Phys. Chem., 96: 3388-3391.
Ramsden JJ (1993).Concentration scaling of protein deposition kinetics.J. Phys. Rev. Lett., 71: 295-298.
Ravichandran S, Talbot J (2009). Mobility of adsorbed proteins: A Brownian dynamics study. J. Biophys., 78(1):110-120.
Retailleau P, Kautt MR, Ducruix A (1997).No salting in lysozyme chloride observed at low ionic strength over a large range of pH. J. Biophysical. 73: 2156-2163.
Ricardo PO (1994).Water-absorbent, A patent survey, J.M. S. Rev. Macromol. J. Chem. Phys. C, (34)4: 607-661.
Roscoe SG, Fuller KL, Robitaille G (1993).An electrochemical study of the effect of temperature on the adsorption behavior of beta-Lactoglobulin, J. Colloid and Interface Sci., 160: 243-251.
Sariri R (1997). Protein adsorption with novel hydrogel biomaterials. J. Iranian Polymer., 7(2): 135-143.
Sariri R, Sabbaghzadeh R (2005). Competitive adsorption of proteins on hydrogel contact lenses. J. CLAO. 27(3): 16-20.
Sariri R, Tighe B (1996). Effect of surface chemistry on protein interaction with hydrogel contact lenses. J. Iranian Polymer., 5(4): 259-266.
Sassi AP, Lee SH, Park YH, Blanch HW, Prausnitz JM (1996). Sorption of lysozyme by HEMA copolymer hydrogel. J. Appl. Polym. Sci., 60: 225-234.
Schaaf P, Talbot J(1989).Surface exclusion effects in adsorption processes. J. Chem. Phys., 91: 4401-4409.
Soltys-Robitaille CE, Ammon DM, Valint PL(2010). The relationship between ontact lens surface charge and in-vitro protein deposition levels. J. Biomater., 22: 3257-3260. Not cited in the work
Song D (2000). Protein Adsorption on Solid Surfaces. USA. In Ph.D Dissertation, University Missouri-Rolla. Provide page number
Tighe BJ, Bright A (1993).The composition and interfacial properties of tears, Tear substitutes and tear models. J. British Contact Lens Association. 2: 57-63.
Voet D, Voet JG, Pratt CW (1999).Fundamental of biochemistry. John Wiley & Jons, Inc. Vol. I. Provide page number
Wiliams D (1990). Concise Encyclopedia of Medical and Dental Materials, Pergaman press Plc.
Yoon JY, Kim JH, Kim WS (1999). The relationship of interaction forces in the protein adsorption onto polymeric microspheres. J. Colloids and surfaces A: Physiochemical and Engineering Aspects.153: 413-419.

Ijome, 2006 is cited in the work, But not cited in the reference section