Hydrogel Contact Lenses

Christina Monis

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Instructor: Prof. G. Selvaduray

San Jose State University

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1. INTRODUCTION

Contact lenses are thin curved disks made out of a clear material. People can use contact lenses to correct their vision or change their eye color. They can also be used in theatres or movies for special effects. Athletes can use specially designed contact lenses to enhance certain colors. For example: Tennis players can wear them to highlight a tennis ball. Contact lenses cover the pupil and iris and are held in place by surface tension caused by tears on the cornea. There are more than 24 million contact lens wearers in the United States.(1) Some people may prefer to choose contacts over glasses because glasses may be too heavy or need wiping. Other people may be required to wear contact lenses therapeutically to correct medical conditions where the cornea is deformed. To avoid the risk of infection, contact lens wearers must be taught how to correctly cleanse and store the lenses. Types of contact lenses include: Gas-permeable contact lenses, toric contact lenses, hard contact lenses, and soft contact lenses.

Analyzing the history of contact lens material shows an engineering trend of making a more softer and permeable polymer material. Polymer materials consist of long chains of branched or unbranched monomers. The first contact lenses were made out of polymethylmethacrylate (PMMA), referred to as being “hard” contact lenses. PMMA is used in Plexiglas. The material is clear, hard, rigid, and is not gas permeable. PMMA has many methyl groups that keep its chains in place and rigid. Hard contact lenses became commercially available to American’s in the 1960’s.(2) In 1971, polyacrylamide was used to make “soft” contact lenses.(2) This polymer is crosslinked and includes a nitrogen. The material is gel like because it can absorb up to 79% of water.(2) Then in 1979, rigid gas-permeable lenses (RGP) were made.(2) This polymer is a mixture of PMMA, “silicone, and flouropolymers."(2) This material does not contain water and allows oxygen to penetrate through to the cornea. Toric lenses can come in either hard or soft and is used to correct astigmatism.

The purpose of engineering the contact lens to be soft and breathable is to make it comfortable for wearing. The PMMA contact lens is less common now because it is the most uncomfortable, but some people still choose to wear them because they cost less and are durable. Another set back is that oxygen can only get to the cornea when the hard lens moves. RGP's, unlike soft lenses, can resist protein or bacterial deposit. Research and studies are still being done to reduce the friction between the cornea and the lens. Optical Polymer Research, Inc., a company that researches polymers can study the properties of different polymers in application to contact lenses. Physical properties that can be compared are the following: refractive index, oxygen permeability, diffusion constant, wetting angle, specific gravity, hardness, and water absorption %. The materials can be designed to last from 2-4 weeks or be disposable.(1) There is a lower chance of getting an infection with disposables but they are more expensive. There are pro's and con's to each type of lens material and therefore consumers can choose lenses that suit their needs.

2. PRINCIPLE

The most common defects in vision are myopia and hyperopia. “Myopia” is the term used to describe nearsightedness. A person with myopia can see near objects clearly but far objects will seem blurry. “Hyperopia” is the term used to describe the opposite experience. Figure 1. shows how nearsightedness makes far objects blurry. The defective cornea will refract entering light so much that the focal point will “fall[s] short of the retina.” (3)

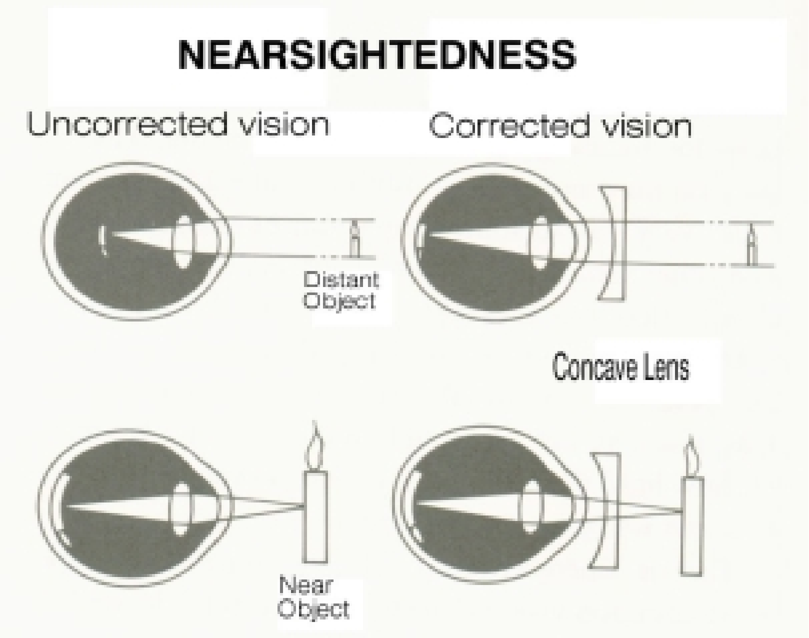

Figure 1. Focal points for nearsightedness. (3)

Figure 2. shows how farsightedness will make near objects become blurry. The defective cornea will not make light converge enough to focus on the retina. Instead, the focus point will land behind the retina.

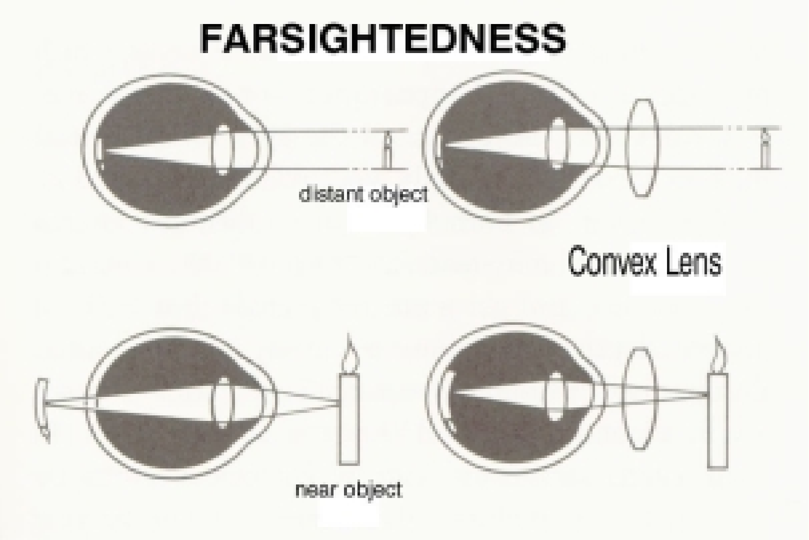

Figure 2. Focal points for farsightedness. (3)

In both cases, the focal point must land on the retina for clear vision. If the papillary muscles can not compensate for the refractive error, external lenses can be used to compensate for the refractive error.

Using materials to correct the refractive error, requires understanding the refraction of materials. Refraction is the bending of light as it exits one material and enters another. The law of refraction follows Equation. 1. Constant n is called the index of refraction and is the "ratio between the speed of light c in a vacuum and the speed of light v in that medium." (4)

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad \text{Equation 1.}^{(4)}$$

Figure 3. shows how applying this equation from air to glass can create a refracted ray within the glass. Similarly, this knowledge can be applied to air and a clear polymer material to create the necessary refractive rays to compensate for the refractive error due to the defective cornea.

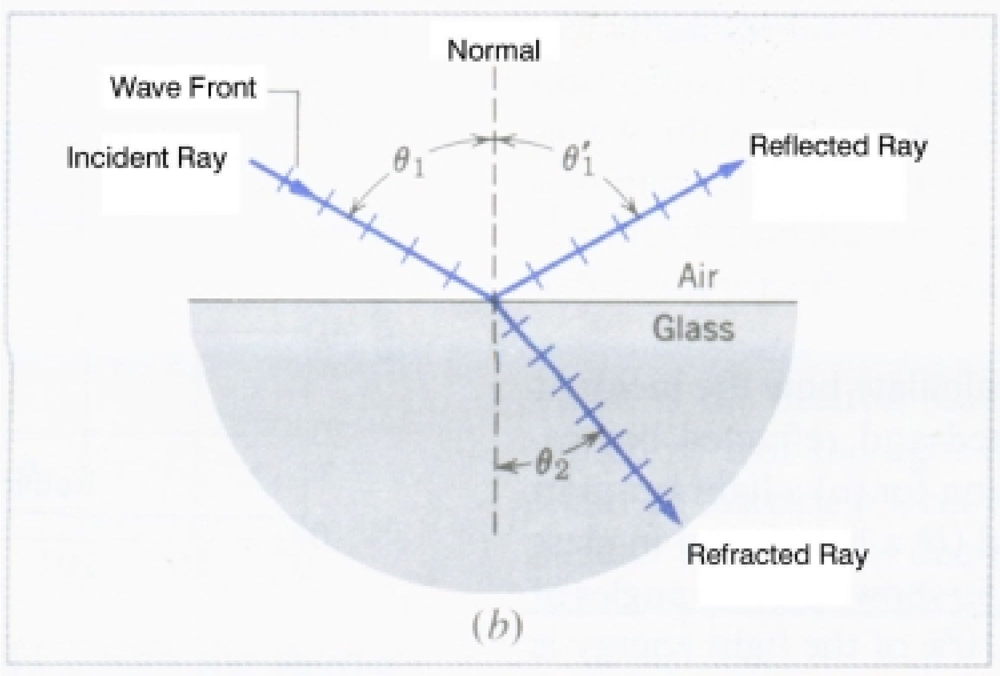

Figure 3. Refraction of light. (4)

Unlike external lenses such as glasses, contact lenses must be engineered to be comfortable to the cornea of the eye. Therefore, it is also very important to be able to control the hardness, elasticity, roughness, wettability, and biocompatibility of its material.

Elasticity, in the case of crosslinked hydrogels, depends on the amount of crosslinking that occurs in the polymer matrix. The more crosslinked the polymer chains, the more rigid and less elastic the material.(5) Polyacrylamide, is a gel used for soft contact lenses. Figure 4. shows a single unit of polyacrylamide. These can be linked together to make a long chain. Crosslinking occurs when sulfer atoms create bridges linking the polymer chains together. The light crosslinking will keep the material soft and allow water absorption.

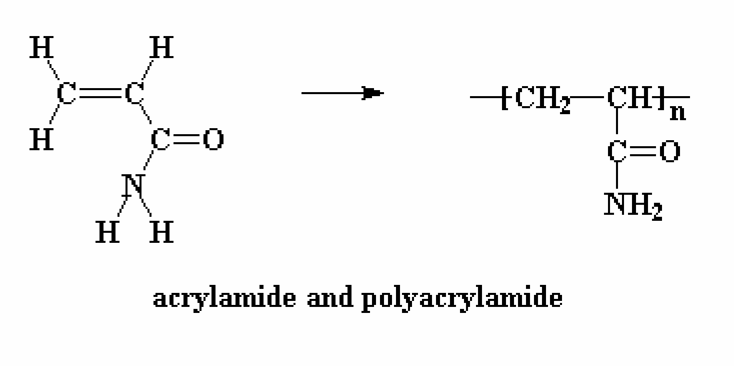

Figure 4. One unit of a polyacrylamide chain. (6)

Roughness of the contact lens needs to be taken into account since it will be rubbing against the cornea of the eye and the eyelid. The following section will describe experiments done by researchers, which show how the physical properties of contact lenses can be studied and controlled.

3. APPLICATION

Engineering soft contact lenses requires knowledge of its optical properties, but for it to be safe for consumers, engineering its wettability, hardness, roughness, and elastic properties are also necessary for comfort.

3.1 Optical Clarity

The refractive index of a hydrogel can be controlled by its water content.(7) Franklin and Wang wrote about the general way of enhancing the optical clarity of a hydrogel matrix. Soft contact lenses, or hydrogels have a refractive index based on the "molar refraction (R), which quantifies the intrinsic refractive power of the structural units constituting that material." (8) Equation 2, the Lorentz and Lorentz equation shows the relationship between molar volume (V), refractive index (n), and molar refraction (R).

$$R = V(n^2 - 1/n^2 + 2) \qquad \text{Equation 2.}^{(8)}$$

"For a neat polymer one can sum the atomic and group refractions (Mr_d) to yield the molar refraction of a repeat unit" (Franklin & Wang 4487).(8) The Lorentz-Lorentz equation will then look like Equation 3.

$$(n2 - 1/n2 + 2)(M/\rho) = \Sigma Mr_d \qquad \text{Equation 3.}^{(9)}$$

M is the "molecular weight of the polymeric repeat and ρ is the density." (9) Franklin and Wang wrote about the general way of enhancing the optical clarity of a hydrogel matrix. They explained that polyacrylamide (PAm), a common hydrogel, is "not homogeneous and should be regarded as random networks."(8) This means that the hydrogel matrix will contain areas of "high point density or high refractive index." (8) Franklin and Wang say that light scattering within a hydrogel can be controlled by controlling the refractive index. Their experiment showed how introducing “additives” of different concentrations into the matrix can be used to control the optical clarity. Franklin and Wang used sucrose as the variable additive and showed that increasing the concentration compensated for the “refractive index homogeneities” within the material.(9) Figure 5. shows how an additive such as Sucrose can add more variability to PAm’s index of refraction. Increasing the sucrose concentration reduced the light scattering.

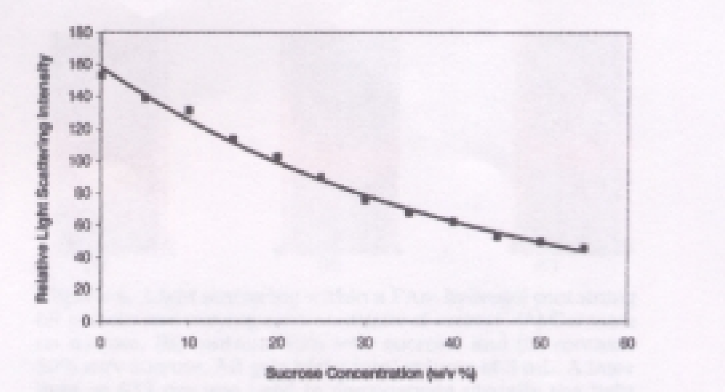

Figure 5. Light Scattering vs. Concentration of Sucrose. (9)

Equation 4. can be used to control the scattering of light within the hydrogel matrix. Franklin and Wang explain that reducing the differences between the refractive indexes of the polymer (n_p) and solvent (n_s) will also reduce the dn/dc and the light scattering of the system.(9) “c” is the speed of light.

$$dn/dc = (n_p - n_s)/c \qquad \text{Equation 4.}^{(9)}$$

Franklin and Wang also introduced the protein bacteriorhodopsin into the matrix and found an overall “chemical compatibility.” (9)

3.2 Hardness and Elasticity

Hardness or elasticity of the hydrogel matrix should also be taken into account when engineering soft contact lenses. Flanigan and Shull wrote a paper on studying the elastic properties of a hydrogel matrix. To study the elasticity as well as the adhesive properties of a polymer gel, they used a glass indenter on an acrylic polymer gel that had been prepared as a thin film on a glass slide. Figure 6. gives an example of how the indenter is applied to a gel layer.

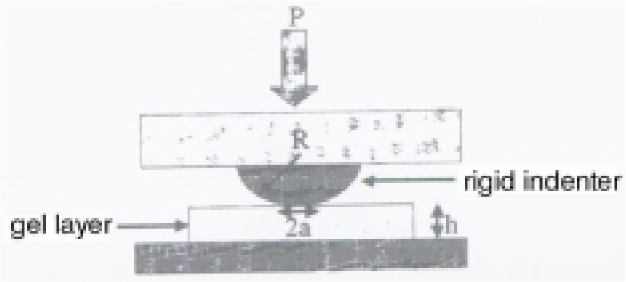

Figure 6. Hardness test with an indenter. (10)

The concept is to find the contact area between the indenter and gel layer and apply it to fracture mechanics equations while taking into account the thickness of the material, the applied load, and radius of the indenter.(10) Flanigan and Shull used fracture mechanics equations to describe the contact between the indenter and gel layer. They derived Equation 5. to describe the "full-friction and frictionless forms of the nonadhesive displacement."(11)

$$\delta' = \delta_h(0.4 + 0.6\exp\{-1.8a/h\}) \qquad \text{Equation 5.}^{(11)}$$

Flanigan and Shull say that the elastic modulus is dependent "on the concentration of polymer in the gel."(10) Knowing this can help find the range of elastic modulus' that they would like to test at. Flanigan and Shull concluded that comparing their method with "adhesion tests performed with soft, elastic caps" showed that their "experimental technique of forming thin elastic layers provides increased flexibility for varying both the polymer volume fraction within the gel and the thickness of the gel layer." (12)

3.3 Hydration and Biotolerance

J. Singh and research associates did research on polymeric hydrogels for soft contact lenses. In their experiment they tested the hydration and biotolerances of various hydrogels. They used Equation 6. to calculate the hydration of the hydrogels. They experimented with changing the ratios of different monomers. The copolymerized samples were prepared using a Co-gamma radiation technique.(13) After the samples reached equilibrium, “hydration was determined by weight difference.”(13)

$$\text{Hydration} = \frac{(\text{Wet wt}) - (\text{dry wt})}{\text{Wet wt}} \times 100$$

Equation 6.(13)

Specific gravity was found by “dividing the weight of the specimen in air by its weight in water.”(13) They measured the hardness using a “Shore D durometer according to ASTM standard D2240-75.” (13) The refractive index of the hydrogels were measured using an Abbe’s refractometer.(13) Wettability was measured using “Goniometer Model 100-00-230” to find the contact angle of a drop of water on the hydrogel surface.(13) They recorded their data in Table 1.

Table 1. Comparison of different hydrogel materials. (14)

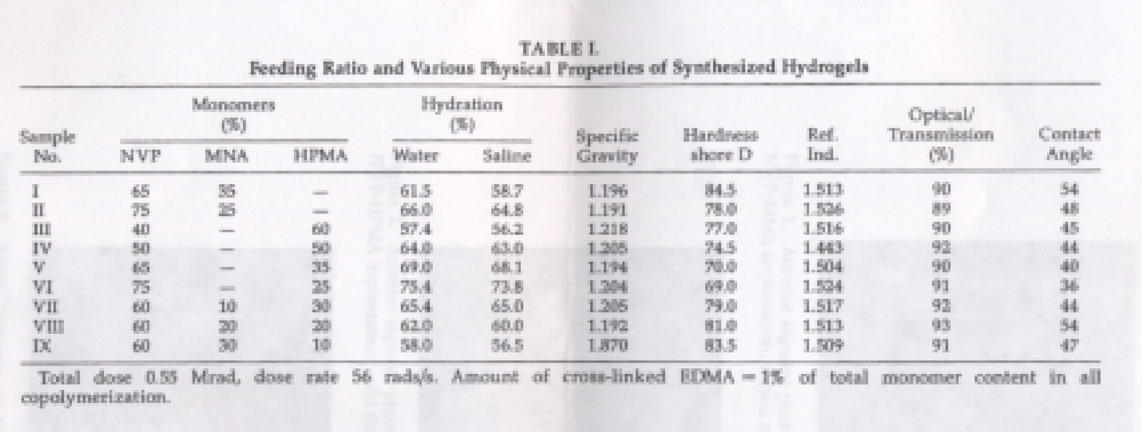

TABLE I.
Feeding Ratio and Various Physical Properties of Synthesized Hydrogels

Sample No.	Monomers (%)			Hydration (%)		Specific Gravity	Hardness shore D	Ref. Ind.	Optical/ Transmission (%)	Contact Angle
	NVP	MNA	HPMA	Water	Saline					
I	65	35	—	61.5	58.7	1.196	84.5	1.513	90	54
II	75	25	—	66.0	64.8	1.191	78.0	1.526	89	48
III	40	—	60	57.4	56.2	1.218	77.0	1.516	90	45
IV	50	—	50	64.0	63.0	1.205	74.5	1.443	92	44
V	65	—	35	69.0	68.1	1.194	70.0	1.504	90	40
VI	75	—	25	75.4	73.8	1.204	69.0	1.524	91	36
VII	60	10	30	65.4	65.0	1.205	79.0	1.517	92	44
VIII	60	20	20	62.0	60.0	1.192	81.0	1.513	93	54
IX	60	30	10	58.0	56.5	1.870	83.5	1.509	91	47

Total dose 0.55 Mrad, dose rate 56 rads/s. Amount of cross-linked EDMA = 1% of total monomer content in all copolymerization.

The researchers found that the gel became more hydrated as the "percentage of N-vinyl pyrrolidone increased in the copolymers."(13) Hardness was found to decrease with the increase of NVP in the "NVP-MMA and NVP-HPMA" copolymer samples.(13) The refractive index of the hydrogel increased as the amount of NVP increased.(13) All the hydrogel samples showed "good transmission of visible light (89-93%)" as shown in the data collected in Table 1.(13)

To study the biotolerance, the researchers placed the samples onto the corneas of rabbits' eyes and checked the result after 90 days.(13) Out of all the samples, Sample No. 1 had the best optical and biocompatible results, being that it stayed "transparent" for 90 days and had "excellent" biocompatibility.(13-14) The other samples had become opaque or caused inflammation.

3.4 Surface of Contact Lenses

Baguet, Sommer, and Minh Duc studied the surface of contact lenses using an atomic force microscope(AFM). It is important to study the surface roughness because it will interact with "tear proteins" and affect the "biocompatibility and spoilage."(15) Protein can accumulate within the hydrogel causing discomfort to the user.

Figure 7. gives an example of how the contact lenses are tested under an AFM. The setup

includes a buffering solution to simulate a contact lens under an “aqueous medium.”(16)

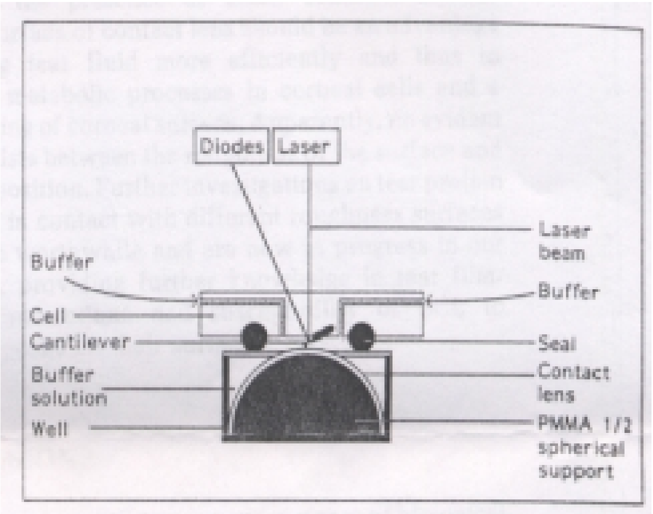

Figure 7. Contact lens sample set-up for an AFM analysis. (16)

They used Equation 7. to calculate the roughness average of the material. The roughness average “represents the mean deviation” of z, where z is the distance from the center line.(16) The center line was calculated from the AFM, “bounded by the roughness curve.”(16)

$$R_a = (1/L)\int_0^L |z(x)|\, d(x)$$

Equation 7.(16)

3.5 Production

Galic and Maus wrote a paper on contact lens fabrication. In their paper, they critiqued the implications of different patents and the application to injection molding of contact lenses. Lenses are generally made by injecting the polymer melt into a mold cavity. Compression will be done using hydraulic cylinders and pressure during the filling of the cavity. Hydrated lenses are “cast and UV cured.”(17) Figure 6. is a schematic drawing of how compression occurs during filling.

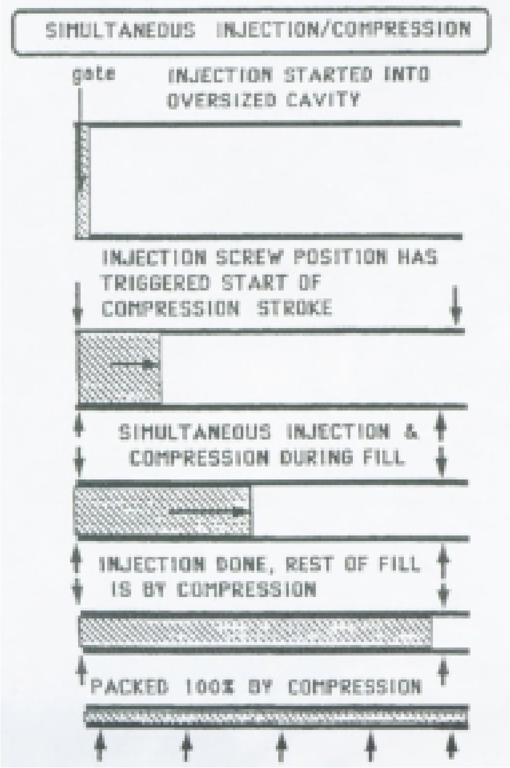

Figure 8. Injection and compression of a polymer melt. (Galic)

According to the School of Optometry in Indiana, hydrogel contact lenses have center thicknesses “from 0.03 to 0.8 mm.”(7) The thickness varies with the power of the contact lens. The diameters of contact lenses range “from 13 to 16mm.” (7) When designing a contact lens it is also important to have the wetting angle be less than 70 degrees to have effective contact with the cornea.(7)

4. CONCLUSION

As it can be seen, researchers have their methods of studying hydrogel contact lenses. Controlling the refractive index and clarity of a hydrogel contact lens relies on the type of polymer and solvent used. Franklin and Wang had showed that reducing the differences between the refractive index's of the polymer and a solvent improved the clarity of the material because it reduced the scattering of light. Flanigan and Shull varied their hydrogel polymer thicknesses when testing for the hardness. This implied that the density of the polymers within a material also affect the elasticity of the material. Therefore, it can be concluded that increasing the amount of solvent (such as water) and decreasing the amount of polymer will result in a more elastic material. Table 1, data from experiments done by Singh et al, showed that varying the types of monomers within the hydrogel matrix and percent of hydration resulted in varying the hardness, refraction index, optical transmission, and contact angle. Polymers can be made with many combinations and have optical properties that vary with the solvent. This is why there is research still being done to test the combinations and find a material that will maximize the comfort and need of the consumer.

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