Chapter 6

Beauty from Contact Lenses beyond Vision Correction

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Contact lenses have recently moved from passively enhancing beauty by their role in replacing spectacles to becoming active beauty aids. The active beauty aid modality occurs when contact lenses change or enhance the color of the wearer’s eyes. Eye color changes with contact lenses can be dramatic when a person with dark eyes appears to have blue eyes. Dramatic eye color changes occur by placing an appropriate, intermittent pattern of opaque pigments on the contact lens that overlays the iris. Underlying iris color aids the pigment in changing eye color. In addition, subtle enhancements are available whereby a person with blue eyes appears to have green eyes. Reactive dyes can make cosmetic lenses that enhance rather than change eye color. Chemistry and technology behind these apparent eye changes will be discussed.
Introduction

The first commercially successful contact lenses were made from PMMA (polymethyl methacrylate). Their success was limited because the wearer's eye shape had to adapt to the shape of the lenses. These lenses were useful for correcting vision but were uncomfortable due not only to their rigidity but also to their minimal ability to transport the amount of oxygen needed to maintain eye health (1). Polymethyl methacrylate lenses are still worn but modern rigid contact lenses are generally made from silicone based materials capable of transporting significantly more oxygen. This increases the probability that the eye will receive sufficient oxygen to maintain health. However, rigid lenses are still generally uncomfortable.

Many rigid contact lenses contain a lightly colored, edge-to-edge visibility tint to aid in inserting them as well as finding them on a sink or carpet. Their relatively small diameters (about 8-10 mm) do not allow them to make significant changes to eye color since this is barely the size of the iris that can reach up to 10 mm depending on the person and illumination. Furthermore, all contact lenses are designed to move on the eye. Lens movement hinders their ability to change eye color since the edges of the iris would be inconsistently covered by the colored portions. Colorant is usually added to rigid lenses by entrapping dyes or pigments during the polymerization process. There is little chance that either dye or pigment colorants will be eluted out of the rigid lens polymer matrix while they are worn since tears do not penetrate the lenses.

Most current commercially available contact lenses are made from hydrophilic materials (hydrogels) that permanently retain water when they are worn. These lenses are flexible enough to accommodate many differences in eye contour among individuals. They are more comfortable than rigid lenses and this has accounted for their wide acceptance. Hydrophilic clear contact lenses have been commercially available for several decades.

The first hydrophilic lenses were made primarily from HEMA (2-hydroxyethyl methacrylate) and contained about 38% water (2). The lenses also contained a small amount of a crosslinking monomer. Water content was increased in later formulations by adding other monomers such as methacrylic acid. Hydrophobic monomers were often added to provide strength. Other hydrophilic materials such as N-vinyl pyrrolidone, polyvinyl alcohol and glyceryl methacrylate have also been used to make hydrophilic contact lenses.

Oxygen is transported through water in hydrogel lenses (3). The amount of oxygen transported is proportional to the amount of water in the lens. Increased oxygen transport is associated with increased health benefits. However, the water content of lenses from these materials is limited and hence the amount of oxygen transported is limited. Unfortunately, the amount of transported oxygen is less than that desired.

Oxygen transport has been increased in newer materials that combine hydrophilic monomers with silicone and perhaps fluorine containing monomers.
These lenses have both hydrophobic and hydrophilic characteristics since they still contain water. The primary oxygen transport medium is through the silicone containing parts of the lens and water is a secondary medium.

Hydrophilic contact lenses offer a suitable platform to alter eye color since they have diameters between about 13.5 – 14.5 mm which allow them to cover most or all of the iris when the lens moves during wear. A hurdle to make colored hydrophilic contact lenses has been adding colorant that will not elute from the lenses. This has been solved either by adhering a printed pattern onto the contact lens or by reacting dyes with the contact lens base polymer. The printed pattern is generally composed of opaque pigments while reactive dyes are translucent.

Colored Contact Lenses

Hydrophilic contact lenses containing colorant fall into the categories of (1) handling tints and (2) cosmetic colored lenses. Cosmetic colored lenses are divided into tints to enhance light eyes and opaque prints to change eye color.

Handling Tints

Handling tints for hydrophilic lenses are analogous to the lightly colored edge-to-edge visibility tints in PMMA and successive generations of rigid lenses. They are usually made by dispersing pigment in the monomer mixture before polymerization to form contact lenses. Pigment is entrapped in the resulting polymer network. Pigments are generally used rather than dyes to prevent elution during wear. Pigment particle size is reduced sufficiently prior to its addition to the monomer mixture so as not to interact with light thereby causing optical aberrations. A patient’s visual acuity while wearing a tinted lens is comparable to a clear lens. Tint aids in inserting lenses and finding dropped lenses. Tint level is low enough that lens color on the eye is not apparent to a casual observer.

Cosmetic Colored Lenses

Tints to Enhance Light Eyes

Enhancing contact lenses are used to give the person wearing them a subtle enhancement to their eye color. For example, a blue eye could become another shade of blue or become green or aqua. These lenses usually do not give acceptable cosmetic effects to people with darker eye colors.
Early work to make hydrophilic contact lenses with enhancing tints was done by exposing them to aqueous dye solutions (4, 5). Dyes were not permanently bound and eluted from the lenses. This was unacceptable and development work focused on other approaches.

The technology quickly evolved to methods that permanently bonded dye to contact lenses. In one approach, HEMA was polymerized with a monomer such as vinyl ethyl maleate that can be photochemically reacted with diazonium double salts (6). The latter reaction permanently bonded dyes to the contact lens.

Pendant hydroxyl groups of HEMA units in pre-formed poly-HEMA contact lens polymers have been used to make tinted contact lenses (7). An aqueous solution of a reactive sulfonyl dyestuff was imbibed into a contact lens and the binding reaction completed by exposing it to sodium carbonate. Dye can be imbibed into the lens in a pattern. For example, the peripheral edge of the lens could remain clear while the central part covering the iris could be tinted. This resultant lens is tinted over the iris but not over the white sclera. In a variation of this process, the same reactive dyestuff can be reacted to monomeric HEMA prior to its use to make a contact lens (8). An example of the dyes used in either method is shown in Figure 1.

Enhancing tints can be used for more than cosmetic effects and have a practical purpose. An example is the ProSoft contact lens. The colorant on the lens is a combination of various dyes that allow the lens to preferentially transmit specific wavelengths corresponding to a desired color, Figure 2. In this example, the transmitted color is similar to that of a tennis ball and other wavelengths are diminished. This should allow the tennis ball to standout from the background. The perceived higher contrast between the tennis ball and everything else should allow the tennis player to more readily focus on the tennis ball.

**Opaque Prints to Change Eye Color**

Otto Wichterle, inventor of hydrogel contact lenses, first disclosed (9) the concept of going beyond enhancing eye color to actually changing apparent eye color.

![Figure 1. Example of a reactive dye used to make enhancing contact lenses.](image-url)
color by making a pigmented rather than tinted contact lens. His method involved drying a hydrated lens then flattening it on a plate prior to adding the pigment in a pattern resembling the iris. This was not a practical method and did not achieve commercial success.

A pigmented eye color changing hydrogel lens was introduced commercially (10). This lens was made by polymerizing a thin, pigmented layer into clear polymer rod. This was lathe cut resulting in a lens with a thin pigmented layer between two relatively thick clear layers. Lens curvature allowed a clear optical zone to be formed because the pigmented layer was relatively thin. The lens did change eye color but was not a commercial success because the pigmented layer was solid and did not resemble a real iris.

The first commercially successful pigmented, opaque print on a contact lens was made by adhering pigment on a lens surface (11). This advance made a contact lens that contained an intermittent, colored, opaque pattern over the iris. The intermittent pigmented pattern left much of the lens covering the iris uncolored allowing the underlying iris to contribute to color change.

Cosmetic lenses have evolved beyond the use of a single color and pattern (12). For example, all the patterns in Figure 3 would be individual colors and applied to a single contact lens yielding a product that combines colors and patterns to closely resemble a human iris. These patterns still contain a significant amount of uncolored space amongst the pigmented pattern. Patterns, colors and uncolored spaces have been combined to make a commercially successful product than gives the eye a natural appearance.
Intermittent, pigmented patterns on a single hydrogel contact lens.

The three patterns, Figure 3, make a contact lens that changes eye color while maintaining a natural appearance. However, a natural appearance is not always the effect desired by truly leading edge, fashion conscious consumers. This group of people can go beyond a natural appearance with products such as Wild-Eyes®, Figure 4.

Figure 4. Examples of leading edge fashion contact lenses.

Another type of colored contact lens is used as a prosthetic device by people with damaged eyes. These lenses combine features of conventional colored lenses and technology used to manufacture Wild-Eyes®. These lenses have a conventional, natural appearing print that may be combined with a completely occluded pupil or one that may be otherwise restricted (13, 14, 15). These lenses allow those who need them to appear in public without drawing attention to a disfigured eye.

Pigments have been attached to lenses in many ways. For example, they can be entrapped in/on the lens using a reactive ink (16). Ink is formulated with pigments, binder polymer with reactive groups such as hydroxyls, solvents and an adhesion promoter such as a diisocyanate. Pigment particle size is reduced to a suitable size prior to ink formulation. Ink is placed on a contact lens, penetrates it and is cross linked thereby entrapping the pigment in an interpenetrating network. In later versions of this technology, the ink is placed on a mold prior to casting a contact lens in the mold (17).

Patterns are placed onto lenses or casting molds by dispensing excess ink onto a plate etched with an appropriate pattern. Excess ink is removed but still retained in etched portions. A soft rubber pad is pressed against the plate to...
transfer much of the ink in the etched portions to the pad. The pad is then pressed against the contact lens or the lens casting mold. Much of the ink from the pad is transferred to the contact lens or the lens casting mold. Pigment can also be placed on a lens with ink jet printers (18).

Printing pigmented inks onto contact lenses or onto casting molds prior to lens formation is the most prominent commercial method to make opaque colored lenses. However, other techniques have been developed to make opaque colored lenses. A method was disclosed whereby an aqueous barium chloride solution was absorbed into a hydrated lens in a selected pattern (19). The lens was then exposed to sulfuric acid to form insoluble, opaque barium sulfate in the lens. Color was added by reacting the lens polymer with conventional reactive dye techniques.

Another method to add opaque pigment to a hydrophilic lens is to soak the lens in a solution of a water soluble vat dye (20). The dye can be imbibed into the lens in a pattern. After the dye is soaked into the lens, it is treated with sodium nitrite to oxidize sulfate ester groups on the dye. The dye is now insoluble in water and permanently entrapped in the lens polymer matrix.

**Pigments Used in Cosmetic Contact Lenses**

Pigments make colored parts opaque and uncoated parts allow the underlying iris to contribute to color change. Pigments were chosen because of their relatively inert nature and good ability to render an surface opaque. Furthermore, they have a long history of successful use in the printing, paint and plastics industries.

Inorganic, metalo-organic and organic pigments are key components of opaque cosmetic contact lenses (16) and will be discussed in greater detail. Examples of inorganic pigments are titanium dioxide, a variety of iron oxide pigments and pearlescent pigments. Blue and green phthalocyanides are metalo-organic pigments and carbazole violet is an example of an organic pigment.

Titanium dioxide, a colorless, crystalline solid, has long been one of the most widely used pigments in printing. Because it strongly reflects most visible light wavelengths, it appears white to the eye. It is also an excellent opacifying material. Its opacifying strength depends on three properties, 1) refractive index, 2) particle size and 3) overall concentration in the polymer. The first is a fundamental property of the particular crystal size. The second, particle size, is controlled to deliver the appropriate opaquing capability. Pigment loading, or concentration is then adjusted in order to balance the need for a cosmetic effect with any tendency to affect desired, polymer mechanical properties. Optimum crystal size for TiO₂ pigments in plastics are between 170 to 240 nanometers.

The family of iron oxide pigments allows us to bring contrast and color into designs. Naturally occurring oxides provide a variety of choices among reds, yellows, browns and blacks. Particle sizes between 100 nanometers to 6 microns are usually found in common use.
Other inorganics are the pearlescent class of pigments (21). Pearlescent pigments appear opalescent because they are sources of multiple light reflection. One example of pearlescent pigments are flat particles of mica encapsulated in titanium dioxide. The multiple reflection of light from such a particle add an impression of depth. These pigments are relatively large and can range from 2 to about 110 microns. Carbazole violet is an organic pigment used in opaque lenses as are the metalo-organic pigments phthalocyanine blue and green.

**Critical Pigment Volume Concentration**

Physical and mechanical properties of the bulk contact lens are extremely important in providing patient satisfaction and performance. These affect comfort and visual acuity experienced by the patient. These critical factors can be affected by the addition of pigments to the polymer. Pigments, of course, also affect the cosmetic effect. Pigment loading then becomes a key factor for appeal and wearability. A balance is needed between having enough pigment loading to obtain the desired colors and designs but at the same time keeping concentrations low enough to avoid negatively affecting lens performance. Molock (22) et al. helps us understand how this applies to contact lens design.

The paint and coatings industry has long understood the interactions of pigments, binders, air, solvents and polymer matrixes. A broad description on the current knowledge in this field, can be found in Patton (23) as he details pigment dispersion and the concurrent properties derived by various formulations. Pigment volume concentration (PVC) obviously can vary between 0 and 100%. Therefore all binder and no pigment is a PVC = 0%, and all pigment no binder = 100%.

In creating a mixture of pigment / binder there are three phases to consider, air, pigment and binder. As you add binder to the pigment, the liquid displaces air until a point is reached where the air is totally displaced with binder. This defines the CPVC (Critical Pigment Volume Concentration). Beyond this point, further addition dilutes the pigment and the particles are allowed to disperse in the increasing liquid volume. The idea of CPVC is then best understood in the following way. Below the CPVC pigment particles are dispersed widely through the system, while above the critical volume, they are closely packed and contain air pockets.

Why this value is important in creating pigment-binder system comes from many empirical observations on the basic properties of the chemical system were trying to color. Basically three types of properties are most important:

- Physical
- Optical
- Permeability
Physical properties such as Refractive Index, Density, Modulus, Strength, Impact resistance etc. are critical for on-eye comfort and dimensional stability. Obviously any negative impact on optical quality that affects visual acuity will not be acceptable. However, in creating natural cosmetic designs, hiding power, tinting strength, gloss and light scattering properties need to be factored into the aesthetic designs.

Permeability has to be considered due to the fact that the majority of cosmetic contact lenses are made from hydrogel polymers and there is added factor of tear fluids and lens care solutions included in the overall polymer matrix.

**Pigment Volume Concentration**

Pigment Volume Concentration (PVC) is simply the volume fraction of pigment versus binder. (without consideration of air, or bulk density). The Pigment Packing (φ) factor takes into consideration of the entire volume. Therefore at CPVC and below, φ = PVC.

In paints a measure of surface finish from matte to high gloss exists. Reduced Pigment Volume Concentration is defined as \( A = \frac{PVC}{CPVC} \). Other key factors optimizing pigments for colors and designs involve;

- particle size
- particle shape
- surface area
- porosity
- agglomeration size / structure
- particle size distribution
- chemical functionality

Each one is a topic beyond the scope of this discussion, but serve as a guide to further investigation in this area. Figure 5 is a visual rendering of the three possible conditions of pigment, binder and air situations.

![Figure 5](image_url)

*Figure 5. L) PVC<CPVC; M) PVC=CPVC; R) PVC>CPVC; Large circles represent pigment particles and small represent binder.*
Safety Considerations

Only FDA approved color additives may be used for coloring contact lenses, and FDA device marketing approval is also needed for colored lenses prior to commercialization in the U.S. Contact lenses, even if used for cosmetic reasons, are medical devices and must be prescribed by a licensed eye care professional. In addition, Federal law (U.S.) prohibits dispensing of contact lenses without a prescription.

The eye care professional will recommend the proper care, wear and replacement regimen of your contact lenses. Improper use of lenses can lead to ocular complications requiring medical treatment. Sharing contact lenses may spread micro-organisms that could result in serious eye health problems.

References
