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Article

The optical possibilities of gelatin

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SUMMARY

Contact lenses have traditionally been manufactured using a variety of plastics: polymers for soft lenses and acrylic or polymethyl methacrylate for hard lenses. There is emerging interest in the use of gelatin for lenses to increase malleability, water solubility, and sustainability as a non-plastic. A predicted difficulty in the use of gelatin is the reduced refractive index (RI). We looked at how acrylic or gelatin changes the RI and focal length in order to see how gelatin lenses would have to be altered for more severe prescriptions. We tested the refractive rays of gelatin and acrylic with both convex and concave lens types to investigate which produced smaller angles of refraction and correspondingly greater focal length. The average RI of the biconvex and biconcave acrylic without Pam, acrylic with Pam, and gelatin were 1.47, 1.496 and 1.36, respectively. Gelatin's lesser angles of refraction produced a longer focal length. The lower RI of the gelatin (0.11–0.136 less than acrylic) directly correlated with its lesser angles of refraction, which produced an overall greater focal length (3.51– 4.38 more than acrylic). Gelatin needs to be thickened, increased in curvature, or mixed with crosslinkers to strengthen the lens. Lens makers will face similar challenges with the switch to gelatin lenses, so they may need to incorporate a larger percentage of solid gelatin concentrate or a plastic alloy in the gelatin to increase the RI, decrease the focal length, and improve the stability of the gelatin.

INTRODUCTION

Since the origin of optics in the 17th century, there has been interest in light refraction in vision corrective lenses (1). Light refraction is the bending of light as it passes through various opaque mediums. In 1621, Willebrord Snell, a Dutch mathematician and astronomer, created a law relating the shape and refractive index of opaque mediums to light refraction (1). Snell's law is used to calculate the exact form of lenses needed to correct eyesight and is still used in corrective lens creation today (2).

Snell's law defines the relationships between the medium's refractive index, the angle at which the light hits the medium, and the effect this relationship has on the resulting light refraction (1, 3). The refractive index of a material is the ratio of c, the speed of light in a vacuum, to v, the speed of light in that material (1, 3). The refractive index of air is 1.000293, water is 1.333 (at 20 °C), collagen (gelatin) is 1.334, and crown glass is approximately 1.523 (4-6). However, the refractive index only accounts for the change in direction after the light is transferred between the transparent mediums at a certain angle. When light passes through a material directly perpendicular to the surface of the material, it passes through the normal line (7). Light on the normal line of any object will not change its direction in the object despite its decreasing speed (7). When light passes into a material at an angle relative to the normal line (the angle of incidence), the angle of light passage in the material changes (the angle of refraction) based on the refractive index. If the medium that light passes through has a refractive index that is greater than the other medium, the angle of refraction will be less (closer to the normal line) than the angle of incidence.

Snell's law is $n_i \sin(\theta_i) = n_r \sin(\theta_r)$, where n_i is the refractive index for the initial medium, n_r is the refractive index for the medium the light passes into, θ_i is the angle of incidence, and θ_r is the angle of refraction (1). The angle of refraction is the angle at which light changes direction through multiple transparent mediums. The angle of incidence is the angle formed when a ray of light and a perpendicular line meet at a surface. Angular shapes have perpendicular normal lines throughout one of their sides (7). However, curved shapes have unique normal lines for each position on their curved sides, which create separate refractions. Concave (minus lens) and convex lenses (plus lens) are used as corrective lenses in glasses (7).

Concave lenses curve inwards with the appearance of an hourglass. When light hits the surface of the lens not on the normal line, the light is refracted outwards **(Figure 1)** (7). Nearsightedness occurs when the eye is longer than normal; light rays come into focus before meeting the retina, the eye's image and light processor. By directing the light outward, concave lenses allow the focal point to move posteriorly to contact the retina (8). Convex (converging) lenses curve outwards and reflect light inwards (7-8). Farsightedness occurs when the eye is shorter than normal, so the focal point occurs too far behind the retina **(Figure 1)** (8-10). With a convex lens, the lens brings the focal point anteriorly to contact the retina (8-10). These lenses work by changing the overall power of the eye's lens system. Concave lenses for nearsightedness act to weaken the lens system or reduce its power in diopters; conversely, convex lenses for farsightedness strengthen the lens system (8-10).

Using Snell's Law, scientists have created ways to adjust each lens to individual prescriptions. Variables that change the light refraction of a lens are the thickness of the lens (edge and center), the curvature/angles of the lens, and the size of the lens (8-10). By changing those variables, lens makers can create different diopters and alter the optical strength (angle of refraction).

Physicists use Snell's Law to invent and modify glasses

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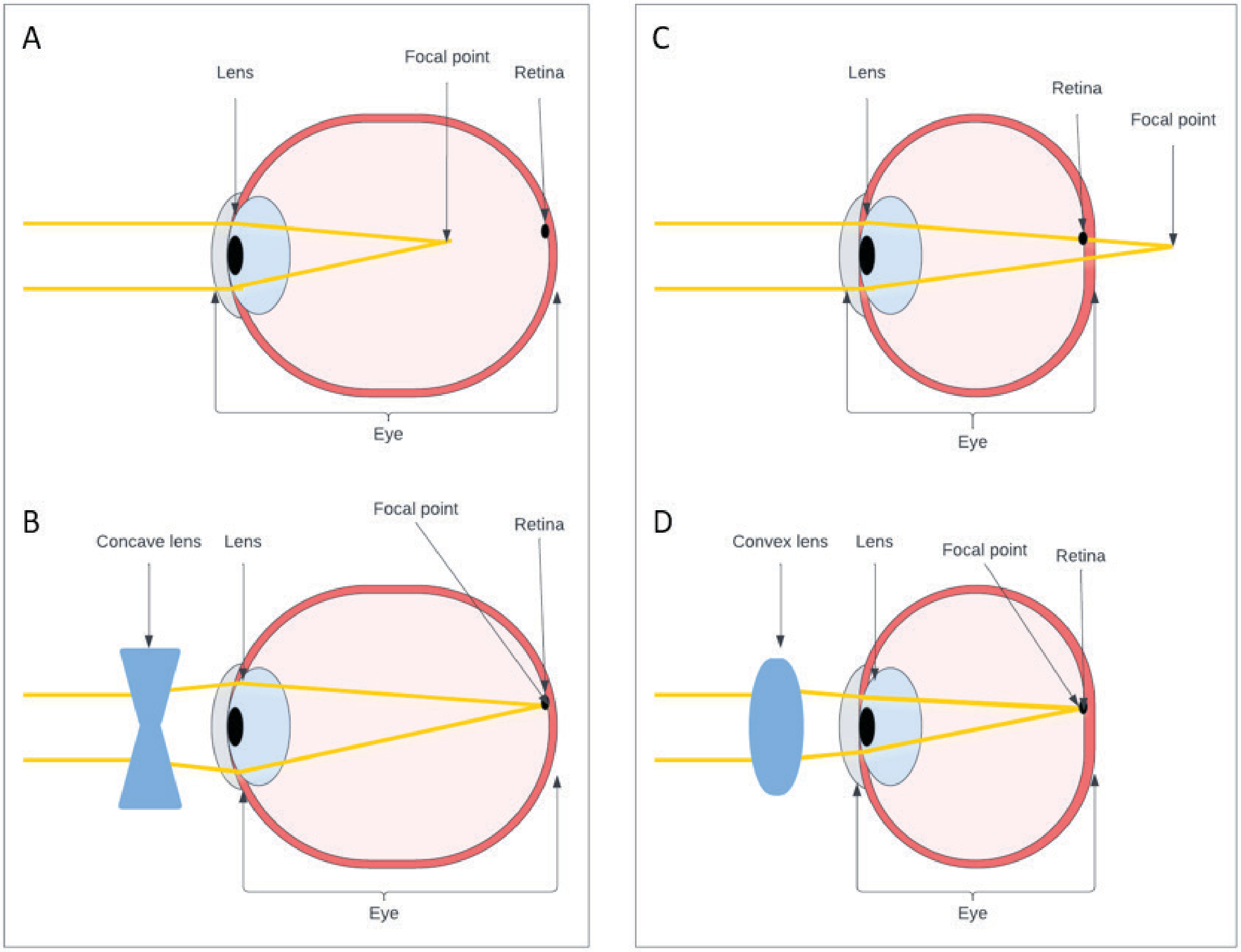

Figure 1: Cartoon of nearsighted and farsighted eyes without and with corrective lenses. (A–B) A nearsighted eye where the eye is longer than normal. In **A**, light rays come into focus before meeting the retina. In **B**, the concave lens directs the light outward, allowing the focal point to move posteriorly to contact the retina. **(C–D)** depict the farsighted eye which is shorter than normal. **C** shows that the focal point occurs too far behind the retina. In **D**, the convex lens is shown to curve outwards and reflect light inwards, which brings the focal point anteriorly to contact the retina.

and contact lenses. Contact lenses have traditionally been manufactured using a variety of plastics: polymers for soft lenses, and acrylic or polymethyl methacrylate (PMMA) for hard lenses (8-10). Yet the past two decades have shown an emerging interest in the use of gelatin and other liquid substances in the place of optical contact lenses. Recent models feature gelatin-based lenses, which have been shown to increase malleability (to accommodate misshapen eyes and heal injuries on the cornea), water solubility (which will prevent dryness), and sustainability in the industry as a non-plastic (11). A difficulty possibly encountered in the transfer from plastic to gelatin may be the significantly reduced refractive index.

In this work, the effect of the refractive index on the angles of refraction and focal length was tested to study how gelatin contact lenses would have to be altered to account for higher prescription strengths. The gelatin mixture used was composed mainly of air, water and collagen (1:1 ratio of Knox gelatin mixture to water), all of which have refractive indices less than that of acrylic. Therefore, we predicted that the angles of refraction would be less for the gelatin than for the acrylic (n_{air} = 1.0003, n_{water} = 1.3333, $n_{collagen}$ = 1.334, $n_{acrylic}$ = 1.4905). We also predicted that the convex acrylic lens would converge at a closer focal point than the convex gelatin lens, and the concave acrylic lens would diverge rays further apart than the concave gelatin lens.

To test this, we investigated the angles of refraction and focal lengths of gelatin and acrylic lens materials for both concave and convex lenses to see which produced a smaller angle of refraction and therefore a corresponding greater focal length. We shone a laser through different lenses made with acrylic or gelatin and recorded the beam trajectories and angles. We found that gelatin has a lesser angle of refraction than acrylic, which produces a longer focal length. These findings show that gelatin has a lower refractive index and therefore needs to be thickened, increased in curvature, or used in a mixture to strengthen the lens. Our results point to challenges that lens makers will face as they attempt to make gelatin lenses and suggest that increasing the resistive index or decreasing the focal length combined with improving the stability of gelatin may help in this process.

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RESULTS

We tested four types of lenses: acrylic biconcave and biconvex and gelatin biconcave and biconvex **(Figure 2)**. We tested the acrylic biconcave lens (without the Pam sheen, the canola oil cooking spray used create a hydrophobic interface between the gelatin and the silicone mold) at three units (on the quarter inch scale graphing paper, 1 box = 1 unit = ¼ inch or 6.35 mm) left of normal and three units right of normal. Measurements along the left of normal gave a refractive index of 1.44 (air to material) and 1.46 (material to air), and measurements along the right of normal gave a refractive index of 1.43 (air to material) and 1.56 (material to air) **(Table 1)**. We calculated the focal length to be -7.23 cm. The acrylic biconvex lens (without Pam) was tested at both three units left of normal and three units right of normal, with measurements along the left of normal giving a refractive index of 1.62 (air to material) and 1.41 (material to air), and measurements along the right of normal giving a refractive index of 1.36 (air to material) and 1.48 (material to air); focal length of 7.26 cm (Table 1). The addition of the Pam sheen did not alter the results for the acrylic lenses in a large way, with the acrylic biconcave with Pam having a refractive index of 1.84 (material to air) and focal length of -7.12 cm, and the acrylic biconvex with Pam having an RI of 1.48 (material to air) and focal length of 7.54 cm **(Table 2)**.

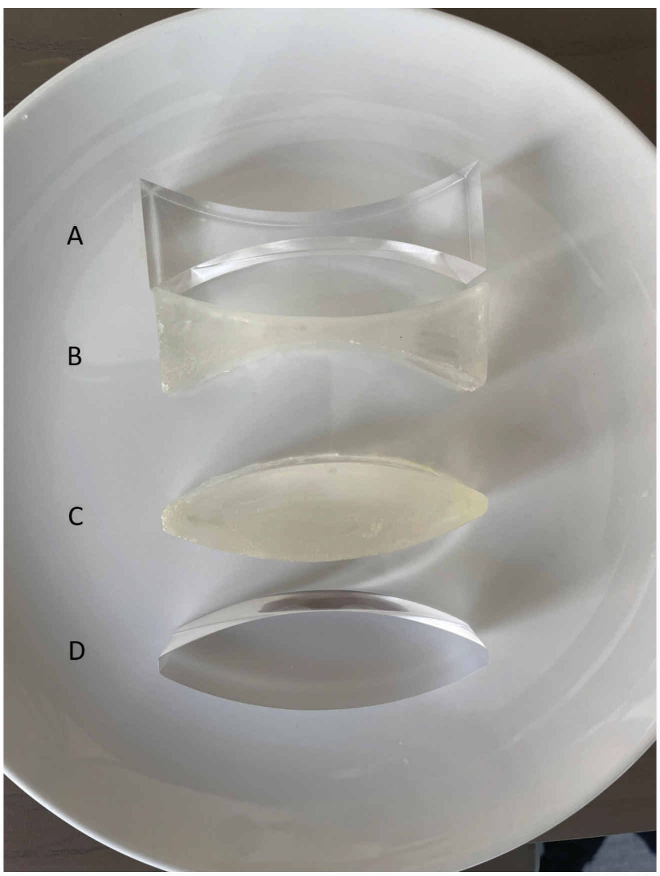

Figure 2: Acrylic and gelatin lenses used in this study. From the top the lenses are: **(A)** acrylic biconcave lens, **(B)** gelatin biconcave lens, **(C)** gelatin biconvex lens, **(D)** acrylic biconvex lens. Acrylic lenses were purchased from Carolina Biological supply. Gelatin lenses were made by first constructing a silicone mold of the acrylic lenses, then by pouring a gelatin solution into the mold and allowing it to harden.

We tested the gelatin biconcave lens at both three units left of normal and three units right of normal **(Table 3, Figure 3)**. We then retested both lenses twice to evaluate for repeatability. To the left of normal, the refractive index range was 1.07–1.09 (air to material) and 1.25 –1.62 (material to air), and measurements along the right of normal gave a refractive index range of 1.71–1.76 (air to material) and 1.25 –1.65 (material to air); the focal length range was -11.36 to -11.86 cm. We tested the gelatin biconvex lens at both three units left of normal and three units right of normal, with measurements along the left of normal giving a range of refractive indices of 1.07–1.35 (air to material) and 1.39–1.44 (material to air), and measurements along the right of normal giving a refractive index range of 1.51–1.59 (air to material) and 1.18 –1.19 (material to air); with an overall focal length range of 9.65 –11.49 cm.

The average of the acrylic without Pam refractive indices was 1.47; for the acrylic with Pam, the average was 1.496 and the gelatin refractive indices were on average 1.36 **(Table 4)**. The percentage error calculations for acrylic without Pam were 3.48% and for acrylic with Pam, 1.733%; for gelatin, the percentage error calculation was 1.949% **(Table 4)**. The focal length of the biconcave acrylic without Pam was 7.23 cm and with Pam, we measured it at 7.12 cm, while the gelatin biconcave lens ranged from 10.76 cm. Focal lengths for the biconvex lenses were 7.26 cm (acrylic without Pam) and 7.54 cm (acrylic with Pam). With gelatin, the focal length ranged from 9.65 cm –11.49 cm.

The lower refractive index of the gelatin (ranging from 0.11– 0.136 less than acrylic) directly correlated with its lesser angles of refraction, which produced an overall greater focal length (ranging from 3.51– 4.38 more than acrylic).

DISCUSSION

Our work demonstrated that gelatin's lesser angles of refraction (due to its smaller refractive index) produced a longer focal length than the acrylic lenses. The measured ratios of the refractive index to focal length provide evidence that larger refractive indices produce shorter focal lengths and vice versa.

Despite the final results matching our expectations, the gelatin caused unexpected difficulties during many of the procedure steps. After the gelatin had hardened inside the mold, it was extremely difficult to remove the lens without breaking it, so we had to redo the process multiple times, finally with Pam cooking spray thinly coated on the sides of the mold, we were able to remove the lens out of the mold (as we learned that Pam helped the lenses come off easier). It was also noted that the gelatin quickly shrunk inside the refrigerator; therefore, the gelatin had to be used relatively quickly after it was made (within 3 hours) for the most accurate results. Since the gelatin lenses were flexible, symmetrically arranging the ends of the lenses was hard, so the tracing of these lenses may have resulted in varied angle measurements and, therefore, varied refractive index measurements. As the ray passed through the gelatin, the line became cloudy and less visible on the paper than the clear one traced with the acrylic lens, most likely due to some unbalanced ingredient ratios in the gelatin mixture. To evaluate the repeatability of these measurements, the experiment was repeated for the gelatin lenses twice, which required making multiple new

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Acrylic Biconcave without Pam — Focal length: -7.23 cm

	Light passage point	Angle of incidence (Θi)	Angle of refraction (Θr)	Refractive index
3 units left of normal	Air to Material	14.3	9.9	1.44
	Material to Air	18.9	28.2	1.46
3 units right of normal	Air to Material	13.2	9.2	1.43
	Material to Air	17.2	27.4	1.56

Acrylic Biconvex without Pam — Focal length: 7.26 cm

	Light passage point	Angle of incidence (Θi)	Angle of refraction (Θr)	Refractive index
3 units left of normal	Air to Material	12.1	7.4	1.62
	Material to Air	17.1	24.5	1.41
3 units right of normal	Air to Material	13.4	9.8	1.36
	Material to Air	16.5	24.8	1.48

Table 1: Angle of incidence and angle of refraction is larger from material to air in acrylic lenses. The angle of incidence, angle of refraction, refractive index, and focal length are shown for the acrylic lenses without pam. A laser was shone through the indicated lens at both three units left and right of the normal line, and the paths were traced on graph paper. The angles of incidence and refraction were measured from the traced line. The refractive indices were calculated using Snell's law and focal lengths were calculated using the standard focal length formula.

Acrylic Biconcave with Pam — Focal length: -7.12 cm

	Light passage point	Angle of incidence (Θi)	Angle of refraction (Θr)	Refractive index
3 units left of normal	Air to Material	12.9	11.3	1.14
	Material to Air	14.3	27.0	1.84
3 units right of normal	Air to Material	11.9	6.0	1.97
	Material to Air	21.9	28.8	1.29

Acrylic Biconvex with Pam — Focal length: 7.54 cm

	Light passage point	Angle of incidence (Θi)	Angle of refraction (Θr)	Refractive index
3 units left of normal	Air to Material	12.1	9.2	1.31
	Material to Air	17.3	26.1	1.48
3 units right of normal	Air to Material	12.9	10.7	1.20
	Material to Air	14.0	24.9	1.74

Table 2: Addition of Pam to the acrylic lenses did not meaningfully change the measured angles or focal lengths from the initial measurements of acrylic without Pam. The angle of incidence, angle of refraction, refractive index, and focal length are shown for the acrylic lenses with Pam. A laser was shone through the indicated lens at both three units left and right of the normal line, and the paths were traced on graph paper. The angles of incidence and refraction were measured from the traced line, and the refractive indices and focal length were calculated.

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Gelatin Biconcave with Pam — Focal length: -11.36 to -11.86 cm

	Light passage point	Angle of incidence (*Θi*)	Angle of refraction (*Θr*)	Refractive index
3 units left of normal	Air to Material	10.6–14.5	9.7–13.6	1.07–1.09
	Material to Air	13.3–14.2	17.8–21.9	1.25–1.62
3 units right of normal	Air to Material	12.0–14.1	6.8–8.2	1.71–1.76
	Material to Air	12.6–16.5	20.4–21.1	1.23–1.65

Gelatin Biconvex with Pam — Focal length: 9.65 cm–11.49 cm

	Light passage point	Angle of incidence (*Θi*)	Angle of refraction (*Θr*)	Refractive index
3 units left of normal	Air to Material	13.1–16.6	12.2	1.07–1.35
	Material to Air	12.1–16	16.9–23.4	1.39–1.44
3 units right of normal	Air to Material	9.2–12.0	6.1–7.5	1.51–1.59
	Material to Air	14.5–16.6	17.2–19.9	1.18–1.19

Table 3: Gelatin lenses with Pam have variable angles of incidence and refraction, with overall focal length longer for biconcave than for biconvex. The angle of incidence, angle of refraction, refractive index, and focal length are shown for the gelatin lenses with Pam. A laser was shone through the indicated lens at both three units left and right of the normal line, and the paths were traced on graph paper. The angles of incidence and refraction were measured from the traced line, and the refractive indices and focal length were calculated.

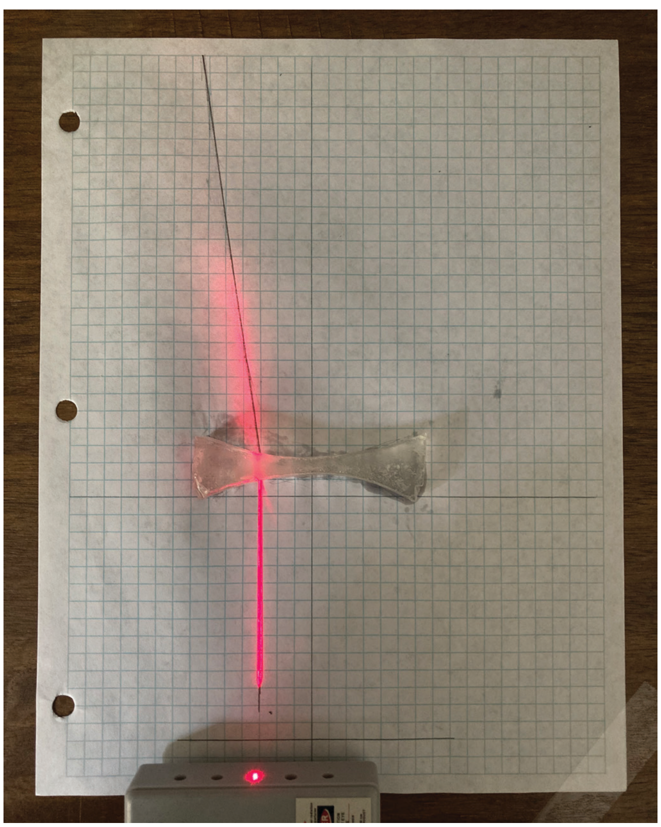

Figure 3: Biconcave gelatin lens ray experimental set-up. The laser box is three units from the normal line and with the pencil tracing along the incident and refractive rays. The angles of incidence and refraction were measured from the traced line, and the refractive indices and focal length were calculated.

lens solutions. In general, the repeated values were similar to initial measurements, however for the biconvex gelatin lens, the focal length calculations actually improved after repeating the experiment (with the later focal lengths of 11.49 cm closer to the expected value, as opposed to the initially obtained value of 9.65 cm). This is likely because the method for extracting the gelatin biconvex lens improved with repeated castings, and there was less breakage of the lens. Despite these limitations, the measurements are consistent with the hypothesis that gelatin lenses were associated with smaller angle measurements and smaller refractive indexes, which explains their longer focal length.

The lower refractive index of the gelatin (ranging from 0.11– 0.136 less than acrylic) showed a direct correlation to the gelatin's lesser angles of refraction, which in turn produced an overall greater focal length (ranging from 3.51–4.38 cm more than acrylic). The estimated ratio for refractive index to focal length of -1:35 for these lens dimensions can be extrapolated to other lens materials that have low refractive indices, which will converge or diverge light less severely than materials with greater refractive indices. In this case, the traditionally used acrylic plastic requires less dynamic curvature and thickness to produce a shorter focal length for a stronger prescription due to its higher refractive index. As it is liquid-based, gelatin has a lower refractive index and for use in contact lenses would therefore need to be thickened, greatened in curvature, or used in a mixture with plastic to strengthen the lens. The gelatin would also need to be made into a close-to-perfect ratio intermixed solution to not induce light blurring.

Future research is necessary to evaluate how different concentrations of the gelatin mixture (instead of a 1:1 ratio) may affect the resultant refractive index and to test how these concentrations affect the resultant flexibility and water

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Acrylic Lenses		Gelatin Lenses	
Average Refractive Index without Pam	1.47	Average Refractive Index without Pam	n/a
Average Refractive Index with Pam	1.496	Average Refractive Index with Pam	1.36
Reference RI for crown glass in the literature	1.523	Reference RI for collagen in the literature	1.334
Percentage Error without Pam	3.48%	Percentage Error without Pam	n/a
Percentage Error with Pam	1.773%	Percentage Error with Pam	1.949%

Table 4: Summary table of refractive indices for acrylic and gelatin lenses. The average refractive index of the acrylic lenses (biconcave and biconvex) and the average refractive index of the gelatin lenses (biconcave and biconvex) are shown. The corresponding Reference Refractive Indices in the literature are shown for comparison, along with the percentage error (by comparing our values to the literature values). Interestingly, the addition of Pam did not result in a greater error for the acrylic lens relative to the literature values for crown glass.

solubility. Gelatin materials form hydrogels readily, but their stability is poor, therefore they are often chemically cross-linked when used commercially (12). The use of a crosslinker in this study would help to ensure the stability of the gelatin lens and improve repeatability (12). Additionally, using a purer (but costlier) collagen unit would improve the homogeneity of the gelatin lens and reduce the blurring effect seen in this experiment. Finally, polymer powder mixtures with water could also be tested as compared to the gelatin concentrate mixture to evaluate their resemblance in properties to hard lenses (traditionally made with acrylic) and/or soft lenses. While challenges in the perfect design of a gelatin lens exist, this research shows that gelatin lenses show promise as a sustainable, environmentally friendly, non-plastic material for use for optical contact lenses.

MATERIALS AND METHODS

Creating the Gelatin Mold of the Convex and Concave Lenses

The acrylic lenses were purchased from a physics supply store and had the following dimensions: Acrylic Biconvex Lens 90mm long x 23 mm at center, and Acrylic Biconcave Lens 90mm long x 10 mm (Acrylic Prism Set, #754930, Carolina Biological Supply, Graham, NC). To make a silicone mold for the gelatin lenses, the mixture was made per manufacturer instructions using a 1:1 ratio of the Alumilite hardener and resin (platinum-based silicone mold-making material, Alumilite Corporation, Kalamazoo, MI). Each of the acrylic lenses (1 biconcave, 1 biconvex) was placed equidistant from the walls of the container and each other. The mixture was poured into the container over the lenses and allowed to harden (~30 minutes). After the silicone mold had hardened, the mold was slowly pulled back from the lenses so as not to damage the mold. Knox gelatin (Associated Brands, Inc., Medina, NY) was prepared according to manufacturer instructions. A thin lining of Pam canola oil cooking spray (ConAgra Foods, Full-Fill Industries L.L.C, Henning, IL) was sprayed into the silicone mold and rubbed with a lint-free cloth to create a uniform sheen to ease the removal of the gelatin lenses. The gelatin mixture was then poured into the mold casts and allowed to harden (3 hours) in the refrigerator. The gelatin lenses were removed from the cast just prior to the experiment.

To test the potential confounding factor of spraying the molds with the Pam canola oil spray for the gelatin lens, the Acrylic lenses were evaluated both 1) without any Pam spray coating and then 2) after coating them with a thin sheen of Pam (similar to the amount on the gelatin lens).

Data Acquisition

Quarter-inch scale graph paper (1 box = 1 unit = ¼ inch or 6.35 mm) was taped by its corners onto a smooth, flat surface. The Laser Ray Box (Item #17167, Educational Science Supplies, xUmp.com; production of up to five red-colored rays, wavelength 650 nm) was connected to a power source and positioned two rows into the foot of the paper. It was exactly perpendicular to the vertical lines so that its central omitted ray aligned with the vertical line 14 units (8.89 cm) from the left edge and 17 units (10.8 cm) from the right edge (for right-handed tracing convenience). The acrylic convex lens was then positioned appropriately with the ray by placing it over the same vertical line and along the horizontal line 14 units (8.89 cm) from the Laser Ray Box. The lens was adjusted to pass the un-angled ray through its normal (no refraction). Each of their positions was traced with a pencil.

After the laser had been moved three units (1.9 cm) left of its prior position, it was activated so that the ray traveled directly over the vertical line. Its path was traced by angling its path along the cardboard lid and checking to see the ray's path on the paper aligned with the traced line. A ruler was used to trace over the line path. The final refracted ray was traced until the end of the graph paper. This procedure was repeated three units (1.9 cm) right of its original position.

This process was repeated twice for each of the lenses/material combinations (acrylic biconvex lens without Pam coating, acrylic biconcave lens without Pam coating, acrylic biconvex lens with Pam coating, acrylic biconcave lens with Pam coating, gelatin biconvex lens, gelatin biconcave lens) on separate sheets of graph paper. During the transferring process, the laser was switched off and the graph paper was replaced. When the gelatin lenses were to be tested, they were removed from the mold using a butter knife and transferred to the graph paper to be positioned/traced carefully so as to not damage the lenses.

Snell's Law Calculations

Measurements were drawn by calculating the incident and refracted angles of each incident/refractive ray paired with a protractor and a ruler. To find the normal line, the protractor was measured 90 degrees from the point of material change

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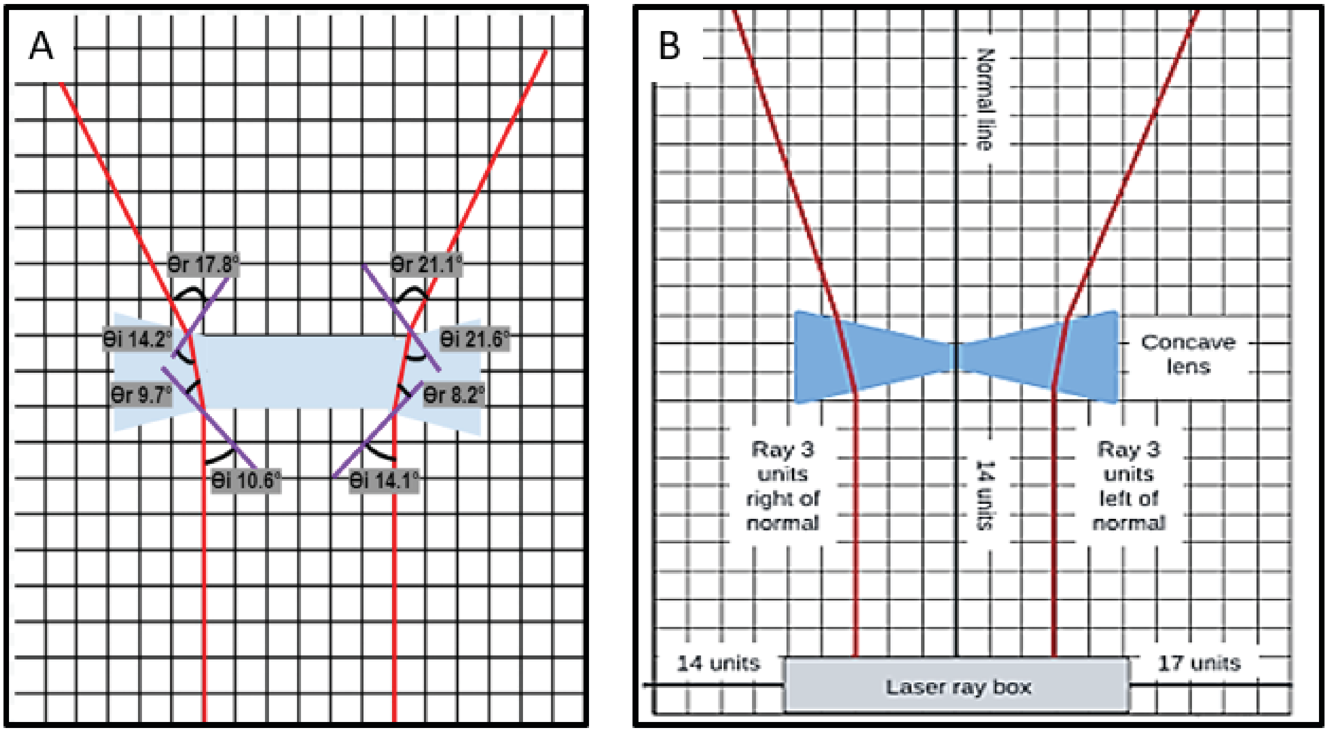

Figure 4: Concave Gelatin Lens Snell's Law calculations. This two-part figure demonstrates the calculations performed after the gelatin lens was removed. In **A**, a protractor was utilized to draw the incident angles (Θ_r= angle of refraction and Θ_i= angle of incidence), and Snell's law to calculate the refractive indices. In **B**, a cartoon of the measured set-up is shown (1 unit is 0.25 inch or 0.635 cm).

(air to material or material to air) **(Figure 4)**. Each pair was recorded for the refractive index using Snell's Law.

The average refractive index and its percent error as compared to the accepted value were found using the prior calculations, where the average refractive index was calculated by using the biconvex and biconcave air to material refractive indices for each material type. The focal lengths of the acrylic lenses and gelatin lenses were measured (the concave lenses' focal lengths were recorded by converging the virtual rays in front of the lens). The equation used to calculate percent error was:

$$\left(\frac{measured\ value - accepted\ value}{accepted\ value}\right) x\ 100$$

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