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REVIEW

# Computer assisted design and finite element analysis of contact lenses

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## Abstract

Contact lenses are an attractive alternative for vision corrections. Their improvement can be achieved by optimizing the geometry, use of new materials, and application of high precision processing technologies. The optimized design can be obtained by computer-aided design, considering the principles of geometrical optics. Inventor Professional and other similar advanced 3D CAD software allows complex approaches, selection of suitable materials with better mechanical/ optical properties. This is useful for the preparation of the virtual design for 3D printing or CNC fabrication. A finite element analysis is also of interest for testing the best design/ material choice.

In this paper, the finite element analysis for a tri-curve contact lens was applied. The selected materials were PMMA and polycarbonate. The applied compressive loads were in the range from 10 to 100MPa. Our results showed that the best scenario was for the polycarbonate, but PMMA also had a high safety factor. The maximum compression load with a reasonable safety factor (of 7-9 depending on materials) was 12MPa.

**Keywords:** contact lens, computer aided design, finite element analysis, PMMA, polycarbonate

## Introduction

Contact lenses have become an attractive alternative for vision correction since their commercial introduction. A continuous research work was dedicated to the improvement of the materials used for their fabrication, the fabrication process itself, and the geometry. Contact lenses are largely fabricated in two ways: CNC lathe cutting, and injection molding [**1**]. Other fabrication technologies are spin-casting and 3D printing [**1,2**]. The CNC method is more time consuming than the injection molding. It also requires more processing steps to obtain the final product.

The 3D printers already made a step forward for industrial applications. They are mainly used for the fabrication of large size objects. The 3D printed contact lens and intraocular lens seem to be a feasible approach, as high-resolution 3D printers for small parts became available [**2**]. The resolution of common

3D printers lies between 10-50 µm, but the *two photon-polymerization* (2PP) technique allows a resolution under 100 nm [**2,3**]. Such a high resolution, below the diffraction limit [**2**], is suitable for the fabrication of small optical devices. The gas permeable (GP) contact lenses are usually custom-made, in accordance with medical prescriptions. The 3D printing could be a solution for special optical devices, in which mass production is not an option. High-resolution 3D printing allows the designing of complex geometries, using more than one material (hybrid lenses, with different optical properties, and colors). Such approach may also allow the integration of electronic devices. Another great advantage provided by 3D technology is the possibility to scan the eye surface and to reconstruct the backside of the lens, allowing a better fitting on the eye.

Three types of properties should be guaranteed for contact lenses: good mechanical properties (compression resistance, wear and fatigue resistance), biocompatibility, and functional (optical) properties as prescribed by doctors. In order to achieve the best properties and novel types of advanced lenses/ devices, materials and technology are important. Computer aided design is necessary and useful.

In this paper, in order to simplify the elliptic shape [**1**], and provide a better comfort we designed using computer a contact lens with a tri-curve back surface. The mechanical behavior of the lens was simulated for the case in which the front face is compressed. For the fabrication of the lenses, two materials were investigated, namely PMMA and polycarbonate.

## Materials and Methods

### *CAD design and materials properties*

The implant was designed in Inventor Professional 2017 (Academic Edition) based on literature data [**1,4**]. The lens curvature can be either calculated, or, much simpler, determined by geometrical construction.

The surface of a free-from-astigmatism cornea can be approximated with an ellipsoid [**1,5**]. The equation (1) for an elliptic curve is:

$$y^2 - 2 \cdot p \cdot x + (1 - \varepsilon^2) \cdot x^2 = 0 \qquad (1)$$

where $p=b^2/a$ ($b$ is the minor radius, and $a$ is the major radius of the ellipse, **Fig. 1**), and $\varepsilon=(1-b^2/a^2)^{1/2}$ is the eccentricity of the ellipse. For $p=7.5$ and $\varepsilon=0.8$ the elliptical curve from **Fig. 2** is obtained.

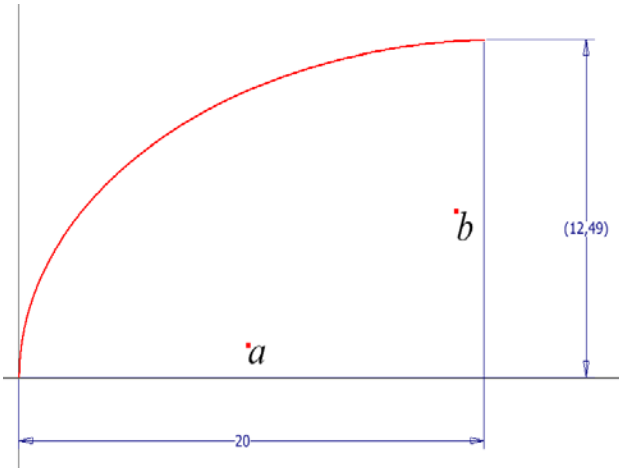



**Fig. 1** The elliptic curve obtained from eq. 1 (dimensions are in mm)

A tri-curve contact lens is designed by approximation of the elliptical curve using three successive circular curves (**Fig. 2**), with the following radiuses: $r_1$=7.695 mm, $r_2$=8.019 mm, and $r_3$=8.285 mm.

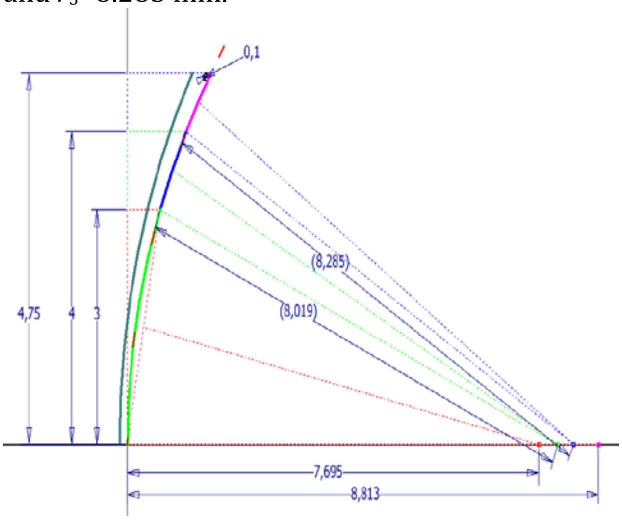



**Fig. 2** Back tri-curve line, and the front line of the contact lens (dimensions are in mm)

The front and back lines of the contact lens are closed with an arc of 0.1 mm diameter (**Fig. 3**). Also, the connection between the front line and the closing arc is smoothed by another arc with a radius of 3.5773 mm (**Fig. 3**)

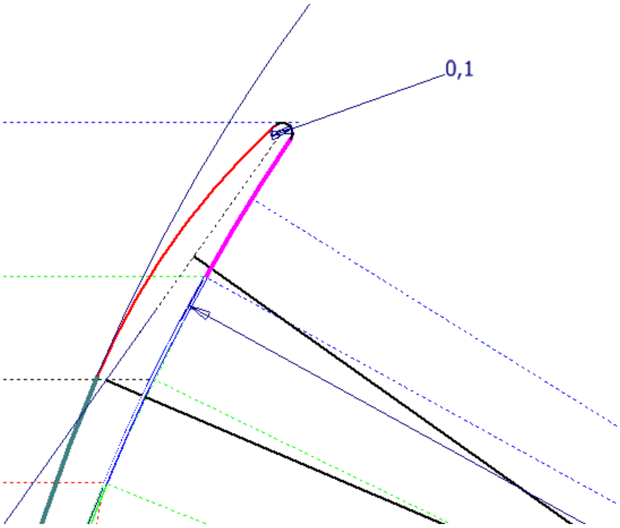



**Fig. 3** The closing arc of 0.1 mm diameter and the smoothing arc (red color)

Finally, the 3D shape of the contact lens will result (**Fig. 5**) by revolving the closed contour from **Fig. 4**.

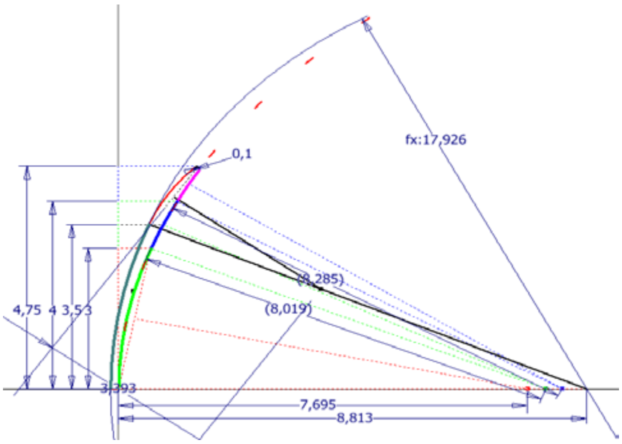



**Fig. 4** The contour used to obtain by revolving the 3D shape of the contact lens

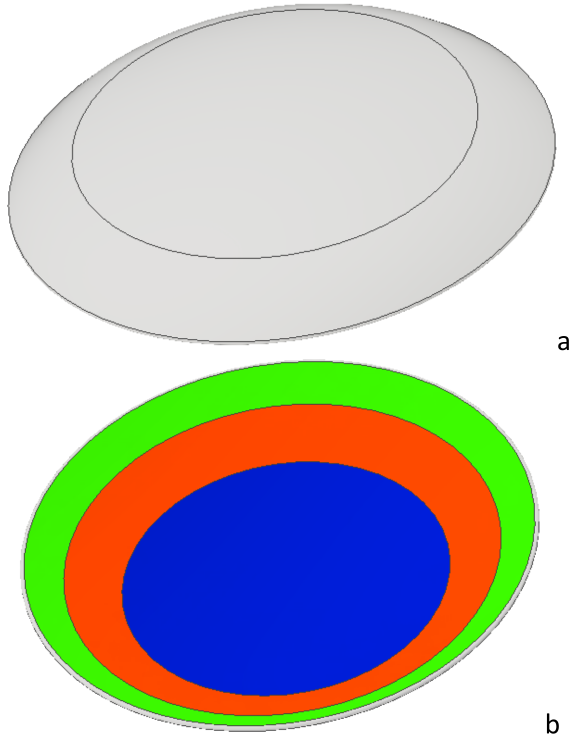



**Fig. 5** Tri-curve contact lens design: **a.** front surface, **b.** back surface

The finite element analysis was performed with the dedicated module from Inventor Professional 2017 (Academic Edition). The selected materials for simulations were PMMA and polycarbonate. All materials were considered isotropic and linearly elastic. Materials' properties were selected from the materials library of Autodesk Inventor Professional 2017 software (**Table 1**).

**Table 1.** Mechanical properties of materials used in the simulation of the contact lenses

| **Material** | **Density [g/ cm³]** | **Young's Modulus [GPa]** | **Poisson's ratio** | **Shear Modulus [GPa]** | **Yield strength [MPa]** | **Ultimate tensile strength [MPa]** |
|---|---|---|---|---|---|---|
| PMMA | 1.188 | 2.74 | 0.35 | 1.77 | 48.9 | 79.8 |
| Polycarbonate | 1.2 | 2.275 | 0.38 | 0.786 | 62.01 | 68.9 |

***Mesh Settings***

The volumetric-element's (tetra 10 type) average size was set to 0.1 mm, grading factor to 1.5, and the maximum turn angle to 60°. "Create curved mesh elements" option was checked. The total number of the resulted elements was 3762, with 6999 nodes.

### *Boundary and Loading Conditions*

The contact lens was considered fixed on its back surface, the area in contact with the eye. Three load magnitudes were analyzed: low (10, and 12 MPa), and high (100 MPa). The static pressure was applied on the front, central surface. The 12 MPa pressure was found to provide a safety factor higher than 7 by successive analyses. The safety factor was checked against the yield strength.

## Results and Discussion

The static simulation results are shown in **Table 2** and **Figs. 6,7**. The simulated mechanical properties are better for the polycarbonate material. E.g., the safety factor is about 30% higher for the polycarbonate case, than for the PMMA one, at 10 MPa load.

**Table 2.** Displacements, Von Mises Stress, and the safety factor for three different loads

| **Materials** | **Displacement [max, µm]** | | | **Von Mises Stress [max, MPa]** | | | **Safety factor [min, ul]** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **10 MPa** | **12 MPa** | **100 MPa** | **10 MPa** | **12 MPa** | **100 MPa** | **10 MPa** | **12 MPa** | **100 MPa** |
| PMMA | 0.6217 | 0.746 | 6.217 | 5.727 | 6.872 | 57.27 | 8.54 | 7.12 | 0.85 |
| Polycarbonate | 0.682 | 0.8184 | 6.82 | 5.613 | 6.735 | 56.13 | 11.05 | 9.21 | 1.1 |

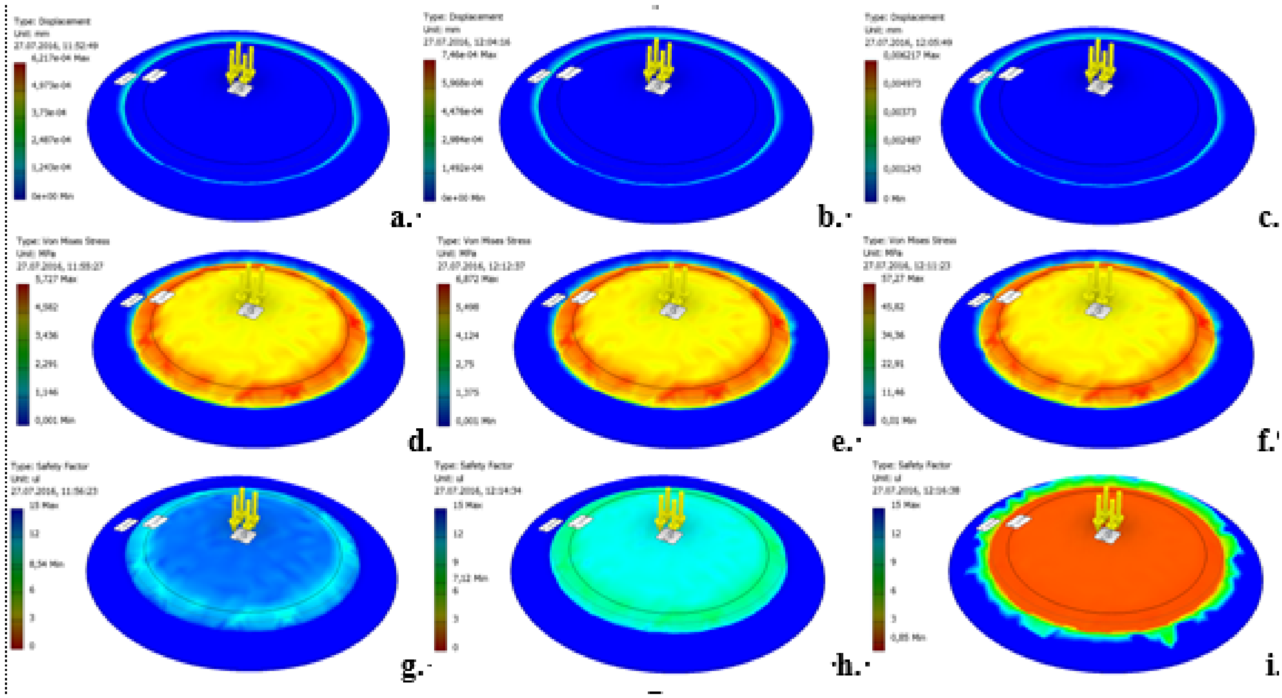
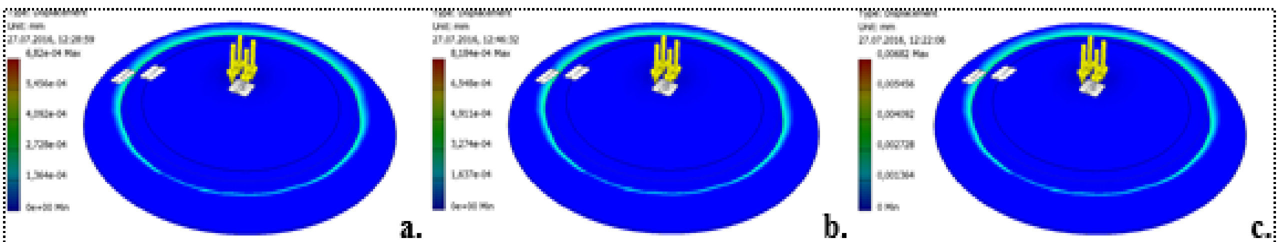



**Fig. 6** Finite element analysis for PMMA: displacement magnitude of the contact lens (for **a.**10 MPa, **b.**12 MPa, **c.**100 MPa), Von Mises Stress with high values in the compressed area (for **d.**10 MPa, **e.**12 MPa, **f.**100 MPa), and lowest safety factor identified in the compressed area (for **g.**10 MPa, **h.**12 MPa, **i.**100 MPa)



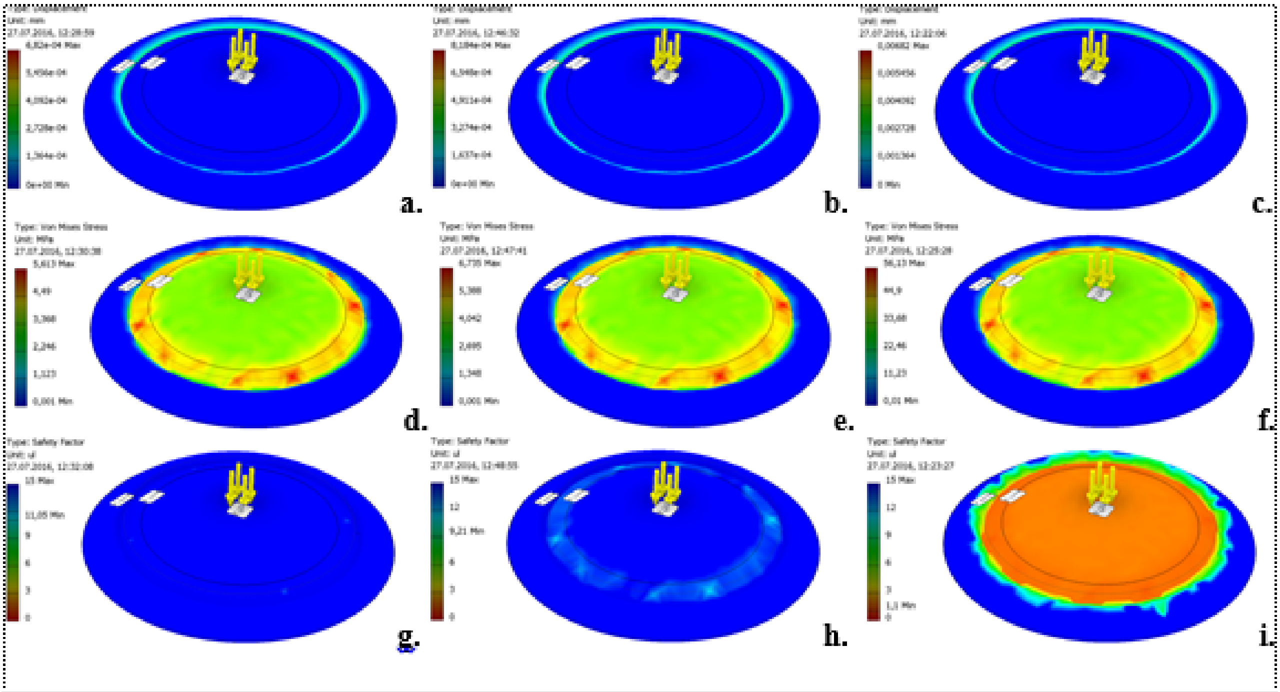



**Fig. 7** Finite element analysis for polycarbonate: displacement magnitude (for **a.**10 MPa, **b.**12 MPa, **c.**100 MPa), Von Mises Stress with high values in the compressed area (for **d.**10 MPa, **e.**12 MPa, **f.**100 MPa), and lowest safety factor identified in the compressed area (for **g.**10 MPa, **h.**12 MPa, **i.**100 MPa)

The critical area (where the stress is maximum) is the central one, where the load is applied. The load does not significantly affect the peripheral area of the contact lens because there is a thicker area than in the center (see the arrow in **Fig. 8**).

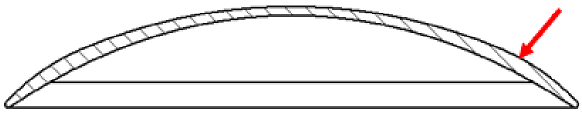


**Fig. 8** Section through the contact lens. Lens thickness is variable (follow the arrow and compare central and peripheral regions of the lens)

The change of thickness and of the curvature acts like a barrier against stress propagation. Noteworthy, a careful manipulation of the contact lens does not involve large loads at all (below 12 MPa). The information obtained by the mechanical simulation can be useful for the processing stages (cutting, polishing, etc.) of the contact lens and during the use of the lens (manipulation by the user). In our simulation scenarios, the implant was tested under a uniaxial force, normal to central front surface of the contact lens, considered the most frequent and critical contact spot.

## Conclusions

A tri-curve contact lens was designed with the help of Inventor Professional 2017. Computer aided design is a useful approach for creating and optimizing the contact lens shape. Once the shape and material are optimized, the virtual object can be further used for computer-aided manufacturing on CNC or 3D printer. In our finite element analysis, we tested two polymeric biocompatible materials, PMMA, and polycarbonate. The contact lens made of polycarbonate shows better mechanical properties than for PMMA. The results are also useful when the automatic manipulation of the contact lens is considered. Further studies should take into consideration the optical features of the designed lens considering the optical properties of the materials.

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