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Evaluation of Optical and Radiation Protection Parameters of High Refractive Index Polymers

Mehmet Kırbıyık[a], Sevim Bilici[a]*

[a]*Department of Opticianry, Vocational School of Health Service, Bandirma Onyedi Eylul University, Bandirma, Türkiye*

* *Corresponding author: Sevim Bilici E-mail: sbilici@bandirma.edu.tr*

ABSTRACT

The optical properties of the prescription and non-prescription (plano) samples of the MR-8 high-index lens were examined by UV/VIS spectrometry. The results showed that the light transmittance of the two MR-8 lens samples examined was over 90%, and the transmittance at the wavelength (~550 nm) to which the human eye is most sensitive was 83.437% and 84.602% for the prescription and non-prescription samples, respectively. In terms of quality of vision, it is expected that the visible light transmittance will be high and the ultraviolet light transmittance will be minimal. It is very important that both the prescription and non-prescription organic MR-8 lenses tested have no transmittance below approximately 398 nm. This means that this lens material protects against UVA and UVB rays, even though it is uncoated. It is also important to reduce the dose to the lens, which is a radiosensitive tissue. In the study, the mass absorption coefficients of MR-8 and Ormix lens materials in the 0.15-2.00 MeV energy range were calculated using the web-based XCOM programme. LAC, HVL, TVL, MFP, RPE and TF values were calculated from the MAC values obtained. At energies below 0.05 MeV, the maximum MAC value was 0.974 and 4.416 for the MR-8 and Ormix lenses, respectively. The RPE and TF values were 0.807-16.235%, 0.996-0.992% for the MR-8 lens and 0.862-55.233%, 0.448-0.991% for the Ormix lens. The results showed that the photon absorption ability of the Ormix lens is relatively better in the region where the photoelectric interaction is dominant. This research is also important in terms of determining the optical and nuclear radiation parameters of the material used in the manufacture of high-index lenses and investigating its effectiveness in reducing the dose to the eyepiece.

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1. Introduction

It is estimated that 1.3 billion people worldwide have visual impairment (uncorrected refractive error). 80% of these visual impairments are preventable. Refractive errors are one of the main causes [1]. These can occur because the eyeball is longer or shorter than normal (myopia, hyperopia), because the cornea is misshapen (astigmatism), or because the lens becomes less flexible after the age of 40 (presbyopia). The most common way to correct vision problems caused by refractive errors is to use eyeglasses, which have the advantage of being the simplest, safest and least expensive [1,2].

The development of technology has led to the improvement of optical instruments that are widely used in the optical industry. In the optical industry in particular, many different materials have been developed to benefit the user in the production of organic (plastic) and mineral types of optical lenses used as vision aids. As mineral lenses are heavier and have lower durability, machinability, and coating limitations, the need for alternative materials such as polymers has increased and many new types of optical polymers have been developed in the optical industry [3–8]. Organic lenses are made from a variety of materials including CR-39 (allyl diglycol carbonate), PC (polycarbonate), polyurethane, polyethylmethacrylate and thiourethane (high-index lenses) [4,6,9]. The refractive index of high-index lenses is higher than other lenses, making the lens thinner and lighter. This is one of the most important needs of the wearer. This is particularly useful for high prescriptions. High-index lenses are made from denser materials, so the same amount of vision correction can be achieved with less lens material than traditional plastic or glass lenses. The thinness, lightness, and strength of a lens are related to the refractive index of the lens material. A high refractive index means that the anterior and posterior curvature of the lens surfaces required for a given optical power is flatter, resulting in a thinner lens [6].

The Abbe number of the lens is another important parameter for spectacle wearers. The Abbe number is related to the dispersion (chromatic quality) of the lens. As the Abbe number increases, the optical quality increases and the chromatic aberration decreases [5,10]. Therefore, when evaluating lens materials for optical performance, high-index and high Abbe number criteria must be met. However, this is not as simple as it seems. Normally, as the refractive index increases, the Abbe number decreases. Researchers have tried various approaches to overcome this typical challenge [3]. The best way to increase the refractive index of optical resins is to add elemental sulphur to the polymer structure, which has the properties of high refractive index, low dispersion, lightness, and good thermal stability [3,6,11]. Thiourethane-based materials are obtained by polymerization of isocyanate compounds and thiol compounds. The popular thiourethane-based materials have high refractive index, low dispersion properties and some even have high Abbe numbers [12,13]. Mitsui Chemicals Inc. has developed the MR™ series of high refractive index lens materials formed from thiourethane-based materials. The MR™ series is popular in the market due to its high mechanical and excellent optical properties. At present, some major optical companies (Hoya, Essilor, Prats) use intermediates to produce their polythiourethanes with equivalent properties [12]. In this study, high-index and high abbe value polythiourethane-based optical lens materials of two different popular brands, listed in Table 1, were analyzed [3,8,11,13–16].

Table 1 Properties of the based material for organic lenses in the study.

Based Material	**MR-8™**	**Ormix (Essilor)**
Refractive index	1.60	1.60
Abbe number	41	41
Density (g cm^{-3})	1.30	1.31
Coating type	None	None
Power	VP and -1.00D	-1.00D

The optical properties of the lenses used to correct the above refractive errors must be good. In addition, the polymer structures of the material used to make the lens must also have good radiation protection potential. Radiation protection properties vary according to the type of material used in optical lenses [17]. The eye has tissue that is sensitive to radiation. Long-term radiation exposure can cause cataracts, opacity and even blindness in the eye. Eye sensitivity to radiation has increased over the last decade. ICRP 118 recommended that the limit be lowered from 150 mSv to 20 mSv per year [18]. It is therefore important to know the effectiveness of lenses in reducing the dose to the eyepiece. If these important requirements are met, the spectacle user's need for refractive vision will be met and ocular health will be protected from radiation. In this study, both optical and radiation absorption parameters of high-index lenses were analyzed. A UV/VIS spectrophotometer was used to analyse the transmittance and absorption spectra of these lenses. The web-based XCOM programme was used to determine the MAC parameter of the thiourethane-based lens material used in the production of these lenses, and other radiation absorption parameters (LAC, HVL, TVL, MFP, RPE and TF) were calculated using the obtained MAC values.

2. Material and Methods

The characteristics of an ideal lens material for use in optical applications include that the lens is light, thin, resistant to breakage and scratching, and that its refractive index, light transmission, light reflection and Abbe number enhance vision performance [12,19]. The Abbe number (ν_D) is the ratio of the angle of refraction to the angle of reflection. A high Abbe number indicates low dispersion, resulting in nearly equal refraction at all wavelengths and high optical quality. The decrease in Abbe number from the center to the periphery in optical lenses is detrimental to the quality of vision. The index of refraction is inversely proportional to the thickness of the lens. To obtain a thin lens, the refraction of the lens must be high. However, as can be seen from equation 1, a lens with high refraction will have a low Abbe value. A low Abbe number means that the further away from the optical center of the lens, the greater the chromatic aberration. The Abbe number should not be less than 30 [3,10,12,19,20].

$$\nu_D = \frac{n_d - 1}{n_F - n_C} \qquad (1)$$

where n_d, n_F, n_C is the value of the refractive index of the material at the wavelengths of 587.6 nm, 486.1 nm and 656.3 nm of the Fraunhofer spectral lines, respectively.

The Abbe number is also very important in the design of achromatic lenses, which focus a range of wavelengths to the same point. The splitting of light into many colours is an indication of the low Abbe number of the raw material from which the lens is made [12,20]. Manufacturers have taken advantage of new types of optical polymers with high refractive index and high Abbe value (low chromatic aberration) to create an ideal lens material. One way to increase the refractive index is to incorporate sulphur atoms into the polymer [3,11]. For this reason, polythiourethane-based optical materials are widely used. At present, some large companies in the optical sector (Hoya, Essilor, Prats) take intermediates and produce their own polythiourethanes with equivalent properties [12]. In this study, high-index and high Abbe value polythiourethane-based optical lens materials of two popular brands were analyzed. Polythiourethane-based materials are obtained by polymerization of isocyanate compounds and thiol compounds. The high-index lens materials analyzed in the study are MR-8 lens material and Essilor's Ormix lens material from the high-index MR series offered to the optical market by Mitsui Chemical Company. MR-8 consists of a trithiol (4-mercaptomethyl-1,8-dimercapt-3,6-diselenaoctane, $C_7H_{16}S_5$) and diisocyanate (m-xylylene diisocyanate, $C_{10}H_8N_2O_2$) formulation [3,8,11,13–15]. Ormix consists of special chemical compounds (54% C, 8% O, 7% N, 24% S, 7% H) obtained from the chemistry of thiourethanes [16]. The optical properties of both lens materials are given in Table 1.

This section consists of both experimental measurement and theoretical calculation for the evaluation of optical and radiation parameters of the lens materials used.

2.1. Measurement

High-index lens materials used as visual aids are expected to have good optical properties. In this section, a UV/VIS spectrophotometer was used to analyse the transmission and absorption spectra of the high-index MR-8 lenses used in the study. Two high-index MR-8 lenses, prescription and non-prescription (plano), were used to interpret the effect of the dioptric power of the glass and the optical properties of the measurement, and measurements were made in the range of 200-800 nm. UV-VIS spectrophotometry is one of the most widely used analytical methods in chemical research for the qualitative and quantitative analysis of organic and inorganic compounds. The basic principle of UV-VIS spectrophotometry is based on measuring the wavelength and intensity of ultraviolet and visible light absorbed by the sample as a function of wavelength [9,21].

The absorption density is formulated by the Beer-Lambert law given by equation 2. The graphing programme Origin 2018 was used to interpret all the results.

2.2. Theoretical Calculations

In addition to good optical properties of the lenses used by spectacle users, the polymer structures of the material used should also have good radiation protection properties to ensure that their eyes are protected. Radiation protection properties vary according to the type of material used in optical lenses [17]. In this section, the radiation absorption parameters of the thiourethane-based MR-8 and Ormix lens materials, which are widely used in optics, are calculated. The results obtained are important for investigating the effectiveness of high-index lenses in reducing the dose to the eyepiece.

Theoretical mass absorption coefficients (MAC) for high-index MR-8 and Ormix lenses were determined using the web-based programme XCOM. From the MAC values obtained, linear attenuation coefficients (LAC) (μ) were calculated according to the well-known Beer-Lambert law given in equation 2. Then the thickness of the absorber that reduces the photon intensity to half (HVL), the thickness of the absorber that reduces the photon intensity to one tenth (TVL) and the values of the mean free path (MFP) that the photon travels through the material (MFP) were calculated. In addition, two other very important parameters, the radiation protection efficiency (RPE) and the transmission factor (TF), were calculated to determine the effectiveness of shielding material. The equations for all the parameters used in the calculation are given in equation 3-8 [9,22–28].

$$I = I_o e^{-\mu x} \qquad (2)$$

where, I_o is photon counts without lens material, I is the counts with lens material and x is the thickness of lens material. The MACs (μ_m) formula used for mixtures and components is the following.

$$\mu_m = \frac{\mu}{\rho} = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \qquad (3)$$

where w_i is the weight fraction of the i^{th} element, $(\mu/\rho)_i$ is the mass absorption coefficient of the i^{th} element.

$$HVL = \frac{\ln 2}{\mu} \quad (4)$$

$$TVL = \frac{\ln 10}{\mu} \quad (5)$$

$$MFP = \frac{1}{\mu} \quad (6)$$

$$RPE = \left(1 - \frac{I}{I_o}\right) x100 \quad (7)$$

$$TF = e^{-\mu x} \quad (8)$$

3. Results and Discussions

High-index lenses have been preferred in the correction of refractive errors because they are both lighter and thinner than standard lenses. On the other hand, high-index lens materials tend to have low Abbe numbers (high chromatic dispersion). This leads to a reduction in the quality of the user's vision [6]. In recent years, some big companies in the optical industry have acquired and extensively developed their polythiourethanes to achieve high-index polymers and high Abbe numbers [12].

The optical transmittance and absorbance of the MR-8 lens, one of the high-index lenses used in this study, were determined using a UV/VIS spectrophotometer for both prescription and non-prescription samples.

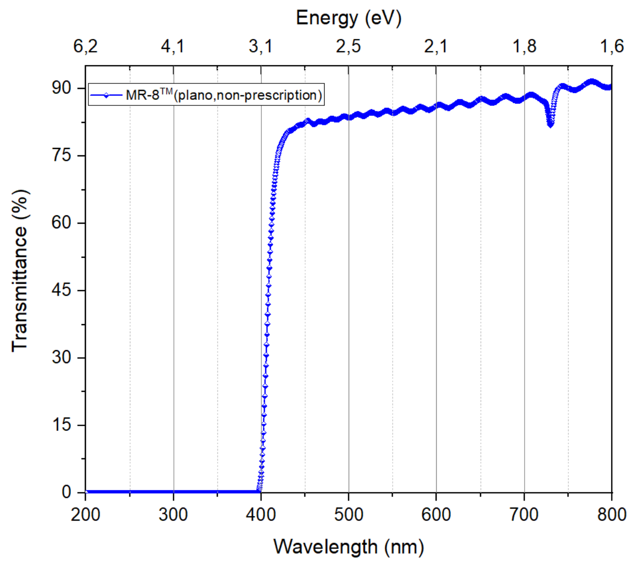

Figure.1. UV/VIS transmittance spectrum of non-prescription high-index eyeglass lens.

Looking at Figure 1, it is very important to note that the non-prescription high-index MR-8 organic lens material has no transmission below 398nm. This means that this lens material protects against UVA and UVB rays even though it is not coated. In Figure 1, the transmittance values increased after 398nm and the maximum transmittance was 91.619%. The transmittance of the lens at 550nm was 84.602%. High transmittance values in the visible range confirm the results.

Figure 2 shows that the amount of absorption in the visible region of the non-prescription high-index MR-8 organic lens material is less than 0.035%. It can be seen in Figure 2 that there is a maximum absorbance at approximately 360nm. This region shows a peak indicating the presence of an excited electron. The ultraviolet and visible spectra of compounds are associated with transitions between electronic energy levels, where an electron is promoted from a low energy orbital in the ground state to a higher energy orbital. The more easily the electrons are excited, the greater the wavelength absorbed; the more electrons are excited, the greater the absorbance [21,29].

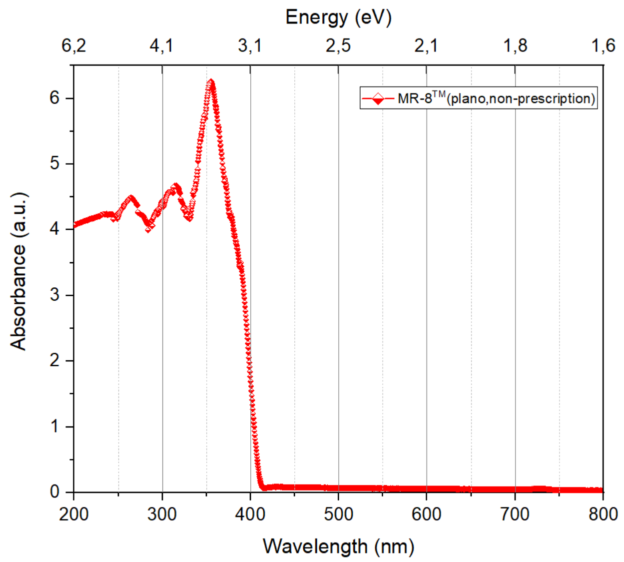

Figure.2. UV/VIS absorbance spectrum of non-prescription high-index eyeglass lens.

Figure 3 shows that the high-index MR-8 organic lens material prescription (-1.00 D) has no transmittance below 397.2 nm. This means that the lens material protects against UVA and UVB rays despite being uncoated, similar to the result in Figure 1. In Figure 3, the transmittance values increased after 397.2 nm and the maximum transmittance was 90.383%. The transmittance of the lens at 550 nm was 83.437%. It can be seen that the absorbance of the high-index MR-8 organic lens material in Figure 4 decreased below 0.041% in the visible region, and it can be seen that the maximum absorbance is around 358 nm.

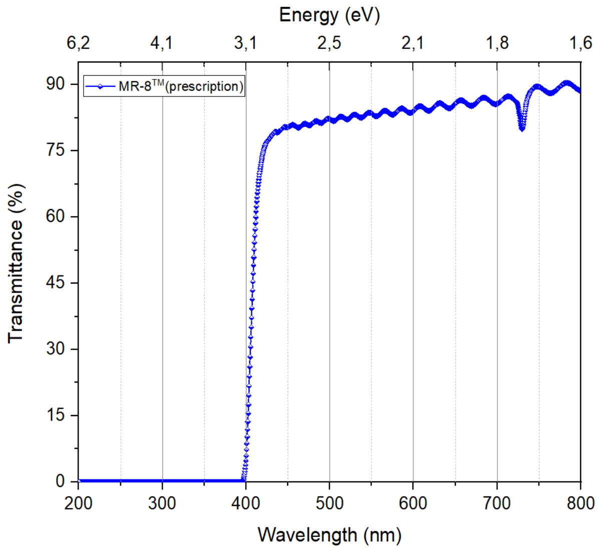

Figure.3. UV/VIS transmittance spectrum of prescription high-index eyeglass lens.

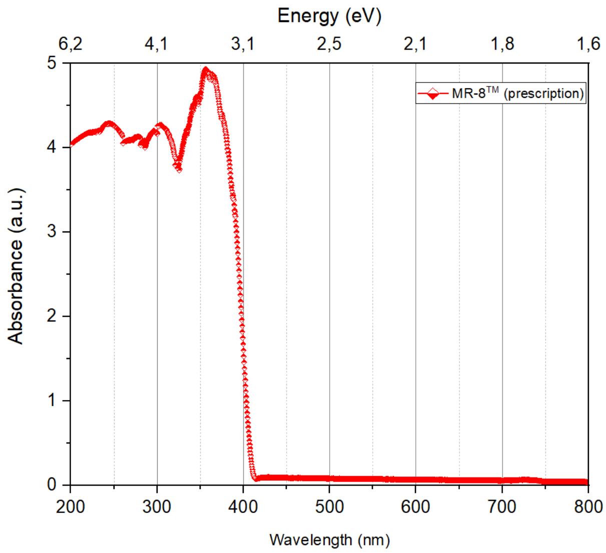

Figure.4. UV/VIS absorbance spectrum of prescription high-index eyeglass lens.

Since the radiation shielding properties vary according to the material used in optical lenses, the next part of the study consists of theoretical calculations to understand how the radiation absorption parameters of MR-8 and Ormix lenses change at photon energies in the range of 0.015-2 MeV.

The Mass Attenuation Coefficients (MAC) for the MR-8 and Ormix optical lenses were theoretically determined using the XCOM web programme developed by NIST, which provides a user-friendly interface with a material description list [24]. Table 2 shows the MAC values obtained at some energies for the MR-8 and Ormix lenses.

Table 2 MAC (μ/ρ) of the high-index lenses obtained by XCOM programme with diferent photons energies.

Energy (MeV)	MR-8^{TM}	Ormix (Essilor)
0.06	0.169	0.243
0.15	0.134	0.149
0.50	0.087	0.093
0.60	0.081	0.086
1.00	0.064	0.068
1.25	0.057	0.061
2.00	0.045	0.048

As shown in Figures 5 and 6, the MAC and LAC values indicate that the photon absorption capabilities of both lens materials are greatest at low energies and decrease with increasing energy. This is because photons have different interactions with matter. These are the Photoelectric Effect (PE) which dominates in the low energy range (0.01 ~ 0.5 MeV), Compton Scattering (CS) which dominates in the medium energy range (0.1 ~ 0.8 MeV) and Pair Production (PP) which dominates in the high-energy range (>1.02 MeV). The probability of photoelectric interactions is associated with Z^{4-5} and $1/E^3$ at low energies, while the probability of Compton interactions is associated with Z and 1/E and the double generation cross-section Z^2 and E at energies above 1 MeV [18,30]. It can be seen from Figures 5 and 6 that both lens materials generally show a similar variation curve. At energies below 0.05 MeV, the maximum MAC value was 0.974 and 4.416 for the MR-8 and Ormix lenses respectively. This indicates that the photon absorption capability of the Ormix lens is better in the region where the photoelectric interaction is dominant. The difference may be because the Ormix lens contains more sulphur in its structure. Sulphur has a high atomic weight.

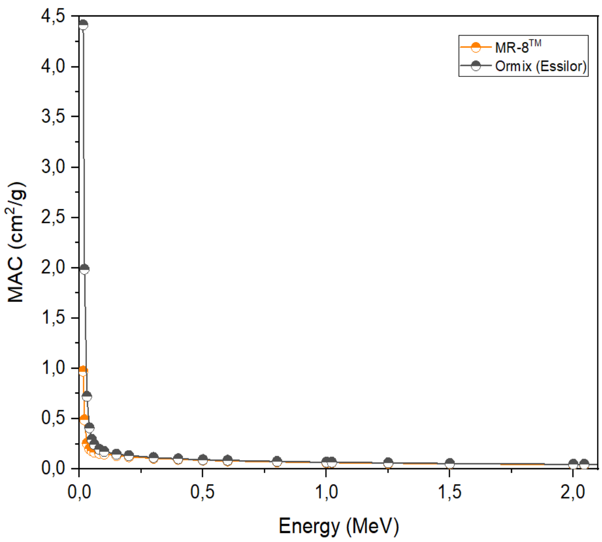

Figure.5. Comparison of MAC values of high-index eyeglass lenses.

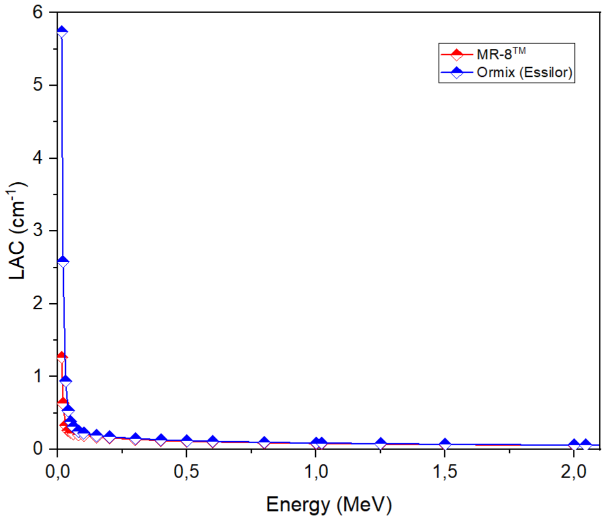

Figure.6. Comparison of LAC values of high-index eyeglass lenses.

As shown in Figure 8-9, HVLs, TVLs and MFPs increased with increasing photon energy as a function of photon energy. Smaller HVL and TVL indicate a better absorber for radiation shielding [23,25,31]. It has been observed that the difference between the HVL, TVL and MFP values of both lens materials is greater at photon energies less than 0.05 MeV, with the MR-8 lens having relatively higher values in this energy range. It can be said that the photon absorption properties of both lenses deteriorate with increasing photon energy.

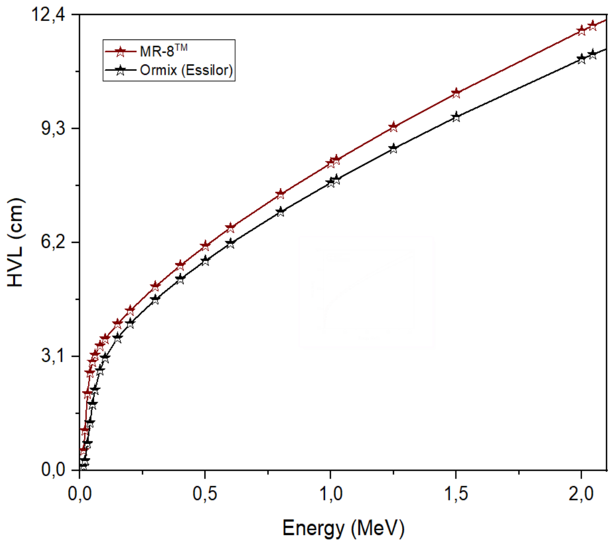

Figure.7. Comparison of HVL values of high-index eyeglass lenses.

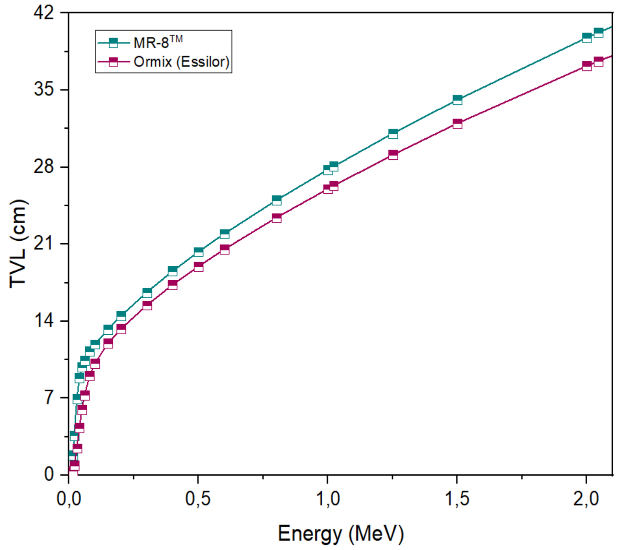

Figure.8. Comparison of TVL values of high-index eyeglass lenses.

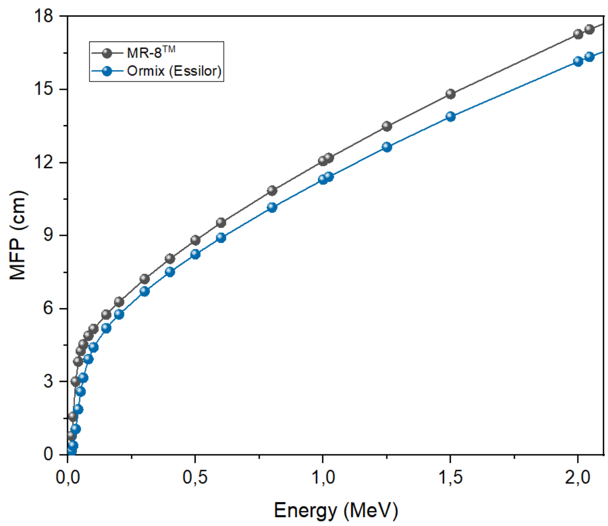

Figure.9. Comparison of MFP values of high-index eyeglass lenses.

Another important radiation protection parameter is the radiation protection efficiency (RPE). Figure 10 shows the variation of RPE with energy. The transmission factor (TF) for MR-8 and Ormix lenses for a thickness of 0.14 cm as a function of photon energy is shown in Figure 11. The RPE and TF values were 0.807-16.235%, 0.996-0.992% for the MR-8 lens and 0.862-55.233%, 0.448-0.991% for the Ormix lens. TF values are inversely proportional to thickness as shown in equation 8. Therefore, as the energy increases, the RPE values decrease and the TF values increase. This is because the higher the energy, the more the rays penetrate.. It was observed that the Ormix lens had the highest RPE and the lowest TF before 0.05 MeV. It can be said that all the results support each other.

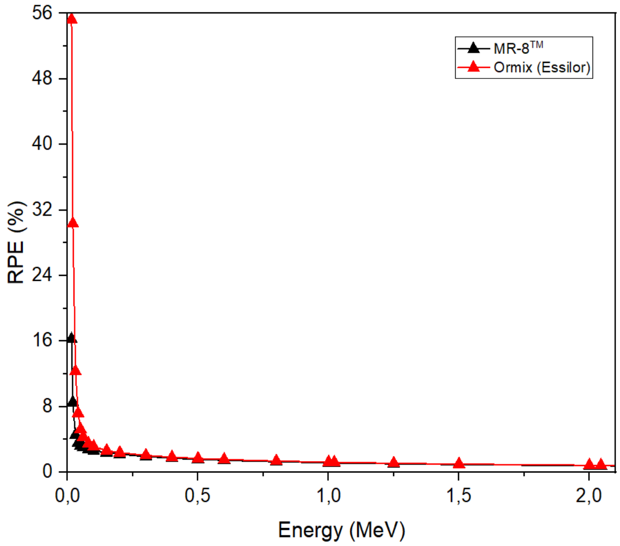

Figure.10. Comparison of RPE values of high-index eyeglass lenses.

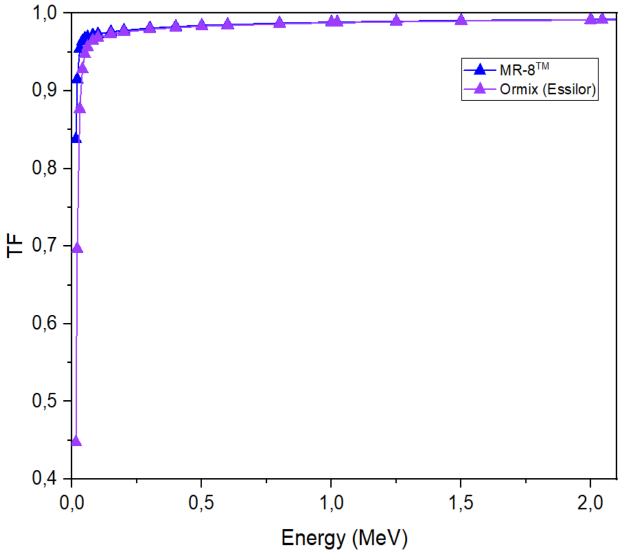

Figure.11. Comparison of TF values of high-index eyeglass lenses.

4. Conclusions

The optical and nuclear radiation absorption parameters of high-index MR-8 and Ormix lens materials were investigated. Therefore, this study is important to evaluate high-index lenses for our eyes in terms of optical clarity and to provide information on radiation protection. It is believed that the results of the research will raise awareness of the need to protect eye health when selecting lenses for spectacle wearers and will contribute to the literature. The results of the study are as follows:

- The maximum light transmission of the high-index prescription and non-prescription MR-8 lenses was 90.383% and 91.619% respectively. It can be said that the very small difference is due to the dioptric power of the lenses and therefore their thickness.
- The photopic vision of the human eye is approximately 97.5 [32]. The light transmission of the lenses used for spectacle users is also expected to be good. Interpreting the prescription and non-prescription readings for MR-8, it can be said that the spectacle user receives approximately 14% and 13% less light than the naked eye. It should be noted, however, that the lenses used in this study to evaluate the transmittance function are uncoated. Although uncoated, it can be said that light transmission is acceptable in this range. Uncoated lenses can reduce light transmission by up to 15% of the available light. This is caused by visible reflections on the front and back of the lens, as well as internal reflections. AR coatings increase light transmission by reducing reflections on the lens [33]. High-index lenses are ideal for anti-reflective (AR) coatings. Multilayer coatings are now being produced. Demir et al. found in their 2023 study that the transmittance of these lenses increased to 99% with multi-layer AR coating [33].
- For both prescription and non-prescription samples of the MR-8 lens, it is very important that the light absorbances for both lenses do not have a transmittance below 397-398 nm as a result of the measurement. This means that although this lens material has no coating, it is shielding with protection against ultraviolet radiation. The American National Standards Institute (ANSI), the International Standards Organisation (ISO) and Prevention Blindness America (PBA) recommend that all lenses provide UV protection at 380 nm [34]. Long-term exposure to UV rays can cause cataracts [32].
- In the study conducted by Ozan et al. in 2017, the MAC values between 0.06-2 MeV for the lens of our eye were found to be in the range of 0.201-0.049 [35]. The MAC values calculated for the MR-8 and Ormix lenses in the same range in this study were in the range of 0.169-0.045 and 0.243-0.049, respectively, and the Ormix lenses were found to be relatively close.
- In the study conducted by Bilici et al in 2023, the maximum MAC values calculated below 0.05 MeV for the CR-39, PC and Trivex lenses were 1.199, 0.978 and 0.831 respectively [18], while in this study 0.974 and 4.416 were obtained for the MR-8 and Ormix lenses respectively. This indicates that the photon absorption ability of the Ormix lens in the region where photoelectric interaction is dominant is relatively better than that of other lens types. The results confirm that the chemical composition of the material has an effect on the interaction of the material with the photon.
- Smaller HVL and TVL indicate a better absorber for radiation shielding. It has been observed that the difference between the HVL, TVL and MFP values of both lens materials is greater at photon energies below 0.05 MeV, with the MR-8 lens having relatively higher values in this energy region.

Other important radiation protection parameters are the radiation protection efficiency (RPE) and the transmission factor (TF). The RPE and TF values were 0.807-16.235%, 0.996-0.992% for the MR-8 lens and 0.862-55.233%, 0.448-0.991% for the Ormix lens. As a result, as the energy increases, the RPE values decrease and the TF values increase. This is because photons with higher energy have greater penetration. It was observed that the Ormix lens had the highest RPE and the lowest TF before 0.05 MeV.

- In addition to the design advantages of the high-index lenses used in the study, the importance of the Abbe number, which is one of the most important optical properties, is a special detail that should be known by the user. In this study, lenses with a high Abbe number (41) were selected from the high-index lenses available on the optical market. From this point of view, it is believed that the study will raise awareness among users.

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Competing interests

The authors declare that they have no competing interests.

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