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FUNDAMENTAL OPTICS OF THE HUMAN EYE AND AGING EFFECTS ON VISUAL ACUITY: AN OVERVIEW

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ABSTRACT

The human eye produces an excellent detailed and accurate image of the external world. What we see, is not as simple as a photographic image. Vision is a dynamic process in which the eyes and brain work together. Thus the human eye may be regarded as an extended part of the brain. The light which enters the eye is converted by the retina into electrical impulses. These impulses are transmitted to the brain where they are analyzed, interpreted and seen. The human eye has a flexible crystalline lens. It changes its power by altering the shape of the lens during accommodation. Visual acuity could be limited by several factors such as scattering of light by small particles in the vitreous humor, refractive errors, photoreceptor density, diffraction and aging. Refractive errors or aging can attribute to variations in the shape of the cornea. Laser surgery may be the choice of treatment to reshape the cornea. In an eye transplant, it is the cornea which is replaced. Presbyopia is an age related problem of the eye which affects almost all the people with the age. This paper provides an overview on the optics of the human eye and its common defects with age.

Key Words: Human eye, Accommodation, Crystalline lens, Refractive errors, Laser Surgery, Aging.

INTRODUCTION

The human eye is the organ which gives the sense of sight. In order to see an object, light is essentially required. Light is an electromagnetic wave. A ray of light can be reflected, refracted, dispersed or absorbed, depending on the different substances it encounters. Eyes obey the laws of refraction. Refraction is the phenomenon which makes image formation possible by the eye. Refraction is an abrupt change in the direction of light rays as they change medium which have different optical properties like water to air or air to cornea. These effects on light propagation occur because light travels at different speeds depending on the medium. The index of refraction of a medium (n) gives an indication of the speed of light in the medium. Fig. 4 shows the index of refraction for different components of human eye. Most of the refraction in the eye takes place at the first surface, since the transition from air into cornea is the largest change in index of refraction which the light experiences. Speed of light in a certain medium is inversely proportional to the index of refraction of that medium. The greater the index of refraction of a medium, the more slowly light travels in the medium. About 80% of the refraction occurs in the cornea and 20% in the inner crystalline lens. Vision begins with light passing through the cornea. The cornea and the lens combine together form a compound lens system in the human eye.

Light sensitive cells/photoreceptors are found in retina. Retina is located at the back of the eye. Photoreceptors in the human retina are classified as cones and rods. Cones are located in the central retina (the fovea) and control color vision. Rods are located outside the fovea and control black/white vision in low-light conditions. Photoreceptors in the retina absorb light and then undergo a chemical change.

This generates an electric potential difference that propagates to the brain. Electrical pulses from various receptors combine and interact in the retina and generate

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electrical signals. These signals contain coded information about the features of the image. The optic nerve carries theses signals from the retina to the visual center of the brain. Many optical changes take place in the human eye with the age which affect the visual acuity [8-11].For well visual acuity, light coming from close objects must be refracted (bend) more than the light coming from distant objects. Therefore, to focus light from close object, the lens becomes more rounded to help the eye to form a clear image. It is just a snapshot of how brain and eyes work together to create vision.

Layers Of Human Eye

Many believe that the 1st layer of the human eye is the cornea, but it is actually the tear film.

The 2nd layer is the cornea, a transparent dome shaped tissue that consists of itself 5 layers starting from the top to bottom. The 3rd layer is the iris. After the iris, there is a transparent crystalline lens. It may be regarded as 4th layer of the eye. The 5th and innermost layer of the eye is the retina. The 6th layer is the choroid, which is filled with blood vessels that help supply blood to the retina. Finally the last layer of the eye is the sclera, a white tissue that covers the whole eye until the cornea. Fig. 1 shows all the layers of the human eye.

Cornea

The cornea is the transparent, dome-shaped window of the eye [1]. The surface of the cornea is where light begins its journey into the eye. Its powerful refracting surface, provides 2/3rd of the eye's focusing power. It has no blood vessels in it. It gets oxygen directly through the air. Oxygen first dissolves in the tears and then diffuses throughout the cornea to keep it healthy[4] . In humans, the refractive power of the cornea (keratometric power) is approximately 43D (D for dioptres unit of refractive power) [3], and has a refractive index of 1.38. Medical terms related to the cornea often start with the prefix "kerat-" a Greek word whose meaning is horn. Most of the refraction of light occurs at the air-cornea surface, because the change in the index is much greater here than at any of the other surfaces inside the eye. The cornea’s outline is not circular, its thickness is not uniform, and its radius of curvature is not constant [1].

The cornea’s function is to gather and focus visual images. Because it is out front, like the windshield of an automobile, it is subject to considerable abuse from the outside world. Scars, swelling, or an irregular shape can cause the cornea to scatter or distort light, resulting in glare or blurred vision. Fig. 2 shows the dome shaped cornea of the human eye.

Aging results in a gradual decrease in the transparency of the cornea. This change is usually great enough to block a significant amount of light. Light at the blue end of the spectrum is blocked more than the light towards the red end. The blue end of the spectrum has light of shorter wavelengths than at the red end. Aging of the cornea also increases the degree of scattering of light that passes through the cornea. Much of the scattered light still reaches the retina, but since it strikes the retina in the wrong places and in a disorganized way, it causes the viewer to see bright areas in wrong places in the field of view. This phenomenon is called glare. With aging, the cornea becomes flatter, reducing the amount of refraction it can cause and making it difficult to see close objects clearly.

Cornea Transplant

During a cornea transplant, an eye surgeon removes a portion of the cornea and replaces it with a new section of cornea from a donor. The procedure is also called a corneal transplant or a keratoplasty. You may need a cornea transplant if your cornea no longer lets light enter your eye properly because of scarring or disease.

Role of Cornea

Light entering an eye first passes through the cornea, then pupil (the dark spot at the center of the colored iris), and then lens.

The cornea must remain clear to see properly. However, a number of problems can damage the cornea, affecting the vision. These include:

- Corneal scarring from trauma and infection.
- Keratoconus. A degenerative condition in which the cornea becomes thin and misshapen.
- Accidents

Types of Cornea Transplants

The cornea contains five layers. Cornea transplants don't always transfer all the layers.

Types of cornea transplants include:
Penetrating (full thickness) cornea transplant.

This involves transplanting all the layers of the cornea from the donor.

Lamellar cornea transplant

During this procedure, some of the layers of the cornea are replaced with the transplant.

Sclera (Sk-ler-a)

The eye is enclosed by a tough white sac, the sclera. This covers the outside of the eyeball (except for the see-through cornea). In humans the whole sclera is white. It is also known as 'white' of the eye. If you look very carefully you can see little red threads, which are tiny blood vessels bringing oxygen to the sclera. Oxygen is the only molecule serving as the primary biological oxidant and is essential for the survival of cells [13]. If you rub your eyes a lot, some of the tiny vessels break, and that is why your eye sometimes looks a little pink. The structure and functioning of the sclera are virtually unaffected by aging, though it becomes somewhat yellow and develops translucent areas that appear as darkened spots. These color changes may have some cosmetic impact.

Iris

This is the colored part of the eye; brown, green, blue, etc. The size of the pupil is adjusted by the iris, a ring of muscular tissue (colored portion of the eye). In bright light, the iris expands to reduce the size of the pupil and limit the amount of light entering the eye [1]. Just as the aperture in a camera protects the film from over exposure, the iris of the eye helps protect the sensitive retina

Pupil

In the middle of iris is the black pupil. Light first travels through the cornea, and then into the pupil. It appears black because most of the light entering it is absorbed by the tissues inside the eye. There are tiny muscles attached to the iris which control its size and help to control the amount of light passing through it. It gets very small in bright light and bigger in dull light. Fig. 3 shows Radial muscle fibers contract in dim light while circular muscle fibers contract in strong light. Fig. 3 also shows variation in diameter of pupil depending on light intensity. Pupil diameter decreases with the increase of age. Fig. 13 shows this relationship [8]. With aging, the number and strength of the muscle cells that cause dilation of the pupil diminish and the thickness and stiffness of the collagen fibers increase. With the advancing Age the cells and fibers in the iris may also slow down the rate at which the pupil dilates when changing from bright to dim light.

Ciliary Muscle & Accommodation

Lens changes shape and increase refractive power to focus objects at different distances on the retina. This is called accommodation [19]. The lens is elastic and can become flatter or more rounded. The more rounded (convex) the lens, the more the light rays can be bent inwards.

The shape of the lens is varied by the small muscles in the ciliary body. A series of fibers (Zunolar fibers) passing from the ciliary body to the capsule of the lens, holding the lens in position and enabling the ciliary body to act upon it.

Ciliary muscles relax to flatten the lens for distance vision and for close vision they contract rounding out the lens. For distant vision Zonular fibers get tighten and lens becomes flatten. For close vision Zonular fibers get relaxed and lens become more spherical/rounded. Fig. 5-a & 5-b shows the function of ciliary body and zonular fibers for distant and close vision.

Aqueous Humor

Aqueous means water, and humour means fluid. After passing through the cornea, light enters the aqueous humor. It has refractive index of 1.34.

Crystalline lens

It is a convex lens made of a transparent and flexible material like a jelly made of proteins. The optical density of the human lens changes during life [10]. The average lens density increases linearly at 400 nm by 0.12 density unit per decade between the ages of 20 and 60 and by 0.40 density unit per decade above age 60 [3]. The mean power of the lens for adults is 18.8D [15].The lens's job is to focus the stream of light coming through the pupil onto the back of eye, known as retina. It changes shape to make sure that the 'picture' on the retina is as clear as possible. This lens has a longer focal length when viewing distant objects and a shorter focal length when viewing nearby objects. It forms a real image of the objects on the retina of the eye. The effective refractive index (ERI) of the lens is 1.44 and it decrease with the aging eye [9]. Fig.14 shows ERI of the lens. With the advancing age the crystalline lens becomes cloudy instead of clear. This condition of eye lens is known as cataract [16-18]. A cataract is not a growth or a film growing over the eye, it is simply the lens becoming misty. Fig 15. shows cataract. The lens is made up mainly of water and protein. Over the time, protein builds up abnormally and obstructs light from passing and being focused on the retina [18]. Cataract is the most common eye disease of the elderly and a major cause of visual impairment worldwide[20].For most people, cataract is a natural result of ageing [17]. The symptoms tend to be a gradual blurring of vision, which if left untreated can result in a total loss of sight. Another age related change in the lens is the loss of elasticity to change its shape. It responses more slowly when it adjusts to near or distant objects. Declining elasticity actually begins some time before age 10 and continues at a steady rate until about age 50. The decline in elasticity decreases the amount of curvature the lens can achieve, and objects must be farther away from the face to be seen clearly. Thus, the smallest distance from the eye at which an object can be seen clearly 'the near point' of accommodation increases. For normal eye the near point is 25cm. The increase in the near point is rapid from about ages 40 to 50, but the rate of change slows during the sixth decade of life. By the age of 60, there is usually no further increase in the near point because the lens loses all the ability to change its curvature. Young people have a tremendous range of accommodation. It will be confusing to attempt to persuade them that 25cm is the near point of comfortable vision as it is normally quoted. Fig. 17 shows the range of accommodation of a human eye, plotted against age. The range is in dioptres, reciprocal metres (metre-1). At age 40 the range is about 4 D, so it may be considered as a 'normal eye' belonging to a person of age 40 with a near point at 25 cm and a far point at infinity. The most dramatic age related change takes place in the lens. Its size, shape and mass alter remarkably. In unaccommodated eye state, centre thickness increases 0.024mm/year and anterior surface radius of curvature decreases 0.044mm/year [8-9].

Fig. 9 shows age related changes in the centre thickness of the lens and radius of curvature.

Vitreous Humor

Light next passes through the vitreous humor. This is a thicker jelly-like liquid which fills the larger part of the eyeball and keeps it in shape. (Vitreous means glassy, because the vitreous humor is very clear, so that light can pass through it). It has the index of refraction as that of aqueous humor i.e 1.34. It is produced by certain retinal cells. It contains very few, no blood vessels, and 98-99% of its volume is water with salts, sugars, vitrosin, and a wide array of proteins in micro amounts.

Retina

Finally light falls on the retina at the back of the eye. The back of the eye is like a movie screen for the images we see, upside down because of the focusing action of the lens, the brain compensates and provides the right-side-up perception.. The retina is made up of very specialized cells called rods and cones. The retina has the highest oxygen consumption rate of any tissue in the body [14].

Rods & Cones

The retina is composed of a thin (~250 µm) sheet of light sensitive cells commonly known as photoreceptors. They are very closely packed. Photoreceptors include about 92 million rods and about 4.6 million cones in each eye (called that because of their shape) [4]. Fig. 16 shows a specimen of rods and cones. Rods can 'see' black and white. Cones can 'see' colours. Rods also allow us to see the shape of different objects. There are three different types of cones that work in bright light; red, blue, and green. Together, these cones process the light waves that come into the eye and let us see many different colors. The rods and cones send all the information they gather through the optic nerve at the back of the eye. The brain then uses the nerve signals to put together a picture of the outside world. The place in the retina where the optic nerve exits is called the blind spot. This is because there are no rods or cones in this area, and if an image is projected onto this part of the retina, we cannot see it. Beginning at age 40, cones decrease in length and many are lost. This decrease in number is greatest in the fovea. The cones that remain in the retina widen to fill the spaces left by degenerated cones. Since the level of visual acuity and color vision are directly related to the concentration of cones in the retina, the declining number of cones with aging contributes to a gradual drop in visual acuity and a diminishing ability to distinguish colors.

Optic Nerve

The electrical messages from the retina travel along the optic nerve to brain. This is the cable connecting the eye to the brain.

Fovea

The most sensitive part of the retina is the fovea, a small section approximately 0.4 mm in diameter, near the center of the retina. It is morphologically specialized for high-acuity vision [12]. It is the part of an image falling on the fovea that is most clearly seen. It contains only cone cells. Approximately 4 mm from the fovea there is a blind spot.

Yellow Spot/Macula

It is situated at the Centre of the retina. Its function is to form an extremely clear image. The fovea is the tiny dimple in the center of the macula like a bulb at the centre of the headlight. (Whole headlight like Macula and Fovea like bulb at its centre)

Choroid

The choroid is a network of blood vessels between the retina and sclera; it supplies blood to the retina and remove waste product. It keeps the interior eye dark and prevents the reflection of light within the eyeball. With the advancing age the blood vessels in the choroid become irregular and decrease the ability to service the retina which results in decreased visual acuity.

REFRACTIVE ERRORS

Refractive errors are vision problems that happen when the shape of the eye does not bend light (Refract) correctly, resulting in a blurred image. Refractive errors are a common reason for reduced level of visual acuity [21-28]. Refractive errors means that the eye can not focus light properly on the retina. Good vision depends on light rays traveling through the eye and focusing sharply on the retina at the back of the eye. As the light rays pass through the eye, they are refracted. If rays coming from a distant object reach the retina in sharp focus, we will see clearly, but if they are not bending in the precise amount, vision will be out of focus, and then we have a refractive "error". This condition is also known as limited visual acuity. Refractive errors are relatively stable between the age of 20-40 years after which there is a shift in the hyperopic direction [8-9].

There are four types of refractive errors[2].

1. Myopia(Shortsightedness)
2. Hyperopia (Farsightedness)
3. Astigmatism (Uneven focusing power)
4. Presbyopia (Age related inability to focus up close)

Myopia (Shortsightedness)

Myopia (shortsightedness) occurs when either the shape of the eyeball is elongated or the cornea is too curved. In a shortsighted eye, parallel rays from a distant object converge before they reach the retina. Despite maximum flattening of the lens, the eye is not able to focus the light rays further back, and on to the retina. The refractive power of the lens is too large; the eye makes the rays converge too soon. A myopic person has clear vision when looking at objects close to him, but distant objects will appear blurred. Fig. 6 shows myopic vision for a person.

Symptoms of Myopia

The main symptom is a difficulty with distance vision [5]. The earlier myopia starts, the more severe it is likely to become. By the time early adulthood reaches, the level of myopia reaches its peak. This means that the vision does not generally get any worse, and indeed stabilizes. Some children do not realize at first that their vision is not as good as it should be. They may be able to read books and do close work well. However, seeing distant objects such as the board at school may become difficult.

Complications

People with severe short sight have a slightly increased chance of developing raised pressure in the eye (glaucoma), detached retina and macular degeneration.

Clinical Treatment Of Myopia

There is no universally accepted method of preventing myopia. The simplest, cheapest and safest way to correct shortsightedness is with glasses. A diverging lens corrects for the shortsighted eye by bending the rays outward just enough that the eye brings them back together at the retina. Diverging lens/Concave lens also known as minus lenses. Contact lenses and laser surgery may be the other choices of treatment. Fig.8 shows myopia and its correction with concave lens.

Hyperopia (Farsightedness)

Hyperopia occurs when either the shape of the eyeball is too short, the cornea is too flat, or the lens cannot become round enough.

In reality, light cannot actually be focused behind the retina. So, the lens changes its thickness (becomes fatter or more rounded) which aims to bring the light into focus on the retina - a process called accommodation. People with farsightedness cannot accommodate fully and light does not focus sharply on the retina. This makes the blurred vision [5]. A farsightedness person may have blurred vision when looking at objects close to him, and clearer vision when looking at distant objects. Fig. 7 shows the hyperopic vision for a person.

Symptoms of Hyperopia

The main symptom is a difficulty with near vision. 'Tiring' of the eyes (asthenopia) is common and long-sighted people may have headaches and uncomfortable vision.

Clinical Treatment Of Hyperopia

The simplest, cheapest and safest way to correct farsightedness is with glasses. Convex lenses (plus lenses) are used to bend light rays slightly inwards. The light rays then have a lesser angle to bend back to focus when travelling through the cornea and lens. As a result, the light rays focus further forward on the retina. Contact lenses and laser surgery may be the other choices of treatment. Fig. 9 shows Hyperopia and its correction with convex lens.

Types Of Laser Surgery For The Treatment Of Myopia & Hyperopia [6-7]

Several types of laser surgery is used to treat Myopia & hyperopia. These include: LASIK, PRK and LASEK. They are similar because the basic idea is to reshape the cornea using the laser to remove a very thin layer. The reshaped cornea allows the refraction of the eye to be corrected.

LASIK®

LASIK stands for **L**aser-**As**sisted **I**n situ **K**eratomileusis. This is the most popular form of laser eye surgery. The laser is used to lift and remove a very thin layer of the cornea. The shape of the cornea is altered to be more curved, so that the light rays can be focused further forward, and on to the retina.

PRK®

PRK stands for **P**hoto-**R**efractive **K**eratectomy. It is an older surgical operation, that has mostly been replaced by newer techniques.

LASEK®

LASEK stands for **LA**ser **S**ub-**E**pithelial **K**eratomileusis. It is an improved form of PRK with some similarities to LASIK. Most of the outer layer of the cornea (the epithelium) is left intact. The LASEK procedure tends to be more painful, and discomfort can last longer than with LASIK.

Astigmatism

Astigmatism is a specific type of blurred vision usually caused by an uneven (non-spherical) contour of the cornea. The cornea is important for focusing, so any shape irregularity can significantly affect the vision. Actually, almost everyone has some astigmatism from birth. It needs correction only if your effort to obtain clear vision creates eyestrain or headaches. Astigmatism is almost always correctable with prescription glasses or with some types of contact lenses. With aging, the cornea becomes flatter or curvature becomes irregular thus reducing the amount of refraction it can cause and making it difficult to see close objects clearly.

Presbyopia

It is an age-related decrease in ability to focus the close objects, caused by a loss in flexibility of the natural lens within the eye. Reading glasses, bifocals, or progressive addition glasses are needed to correct for this particular refractive error. The amplitude of accommodation reaches a peak early in life, then gradually declines. Presbyopia becomes a problem for most people in their forties when they can no longer see clearly to perform near tasks. Accommodation is completely lost in the fifties. The cause of presbyopia has been controversial in recent years, but the majority of investigators believe that it is due to changes within the lens and capsule in which the lens loses its ability to change shape [8]. Fig. 12 shows a relation between age and amplitude of accommodation.

Facts & Information

It is not possible to have myopia and hyperopia at the same time, but you could have either one coupled with astigmatism. Presbyopia, of course, will occur on top of any combination when you reach middle age, or even if you have no other refractive error.

Interesting point: No matter what type or combination of refractive errors blurs your vision, you can always sharpen it by squinting (half-closing your eyes). By looking through a tiny hole, you can always improve visual acuity.

Fig. 1. Layers Of Human Eye

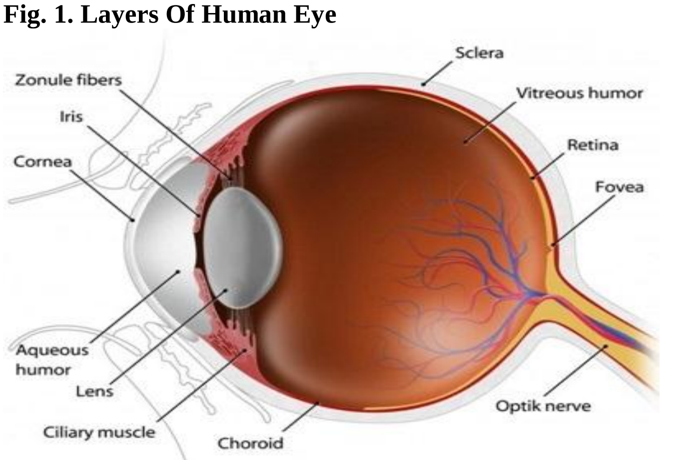

Fig. 2. Cornea Of Human Eye

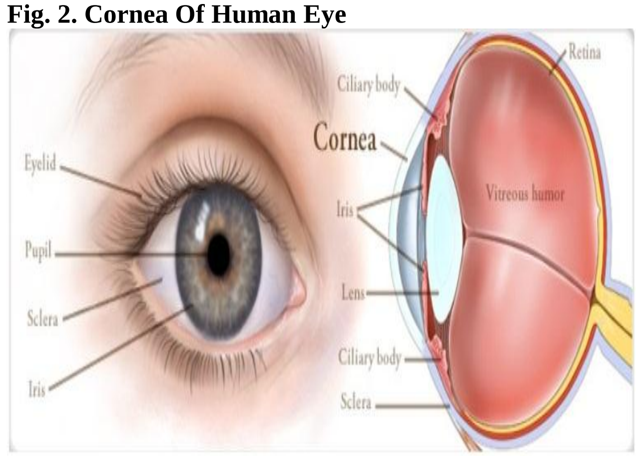

Fig. 3. Variation In Diameter Of Pupil Depending On Light Intensity.

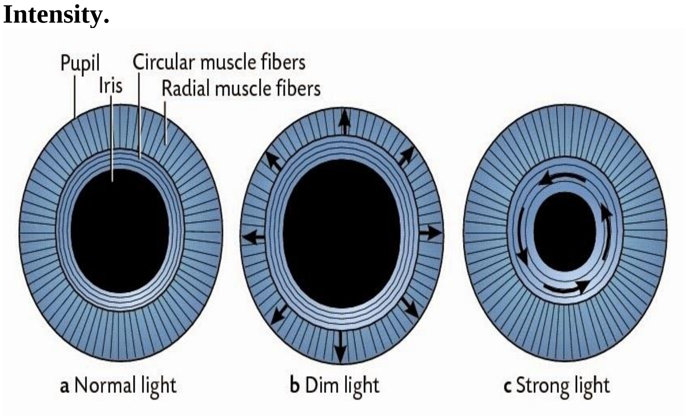

Fig. 4. Refractive Indices (n) & Sizes Of Different Parts Of The Human Eye

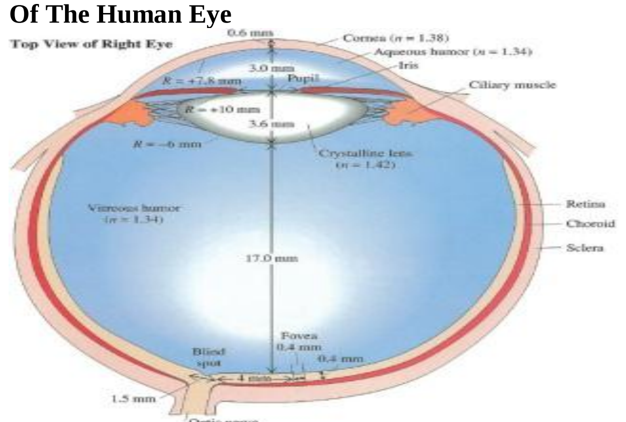

Fig. 5. Function of Ciliary Body & Accommodation

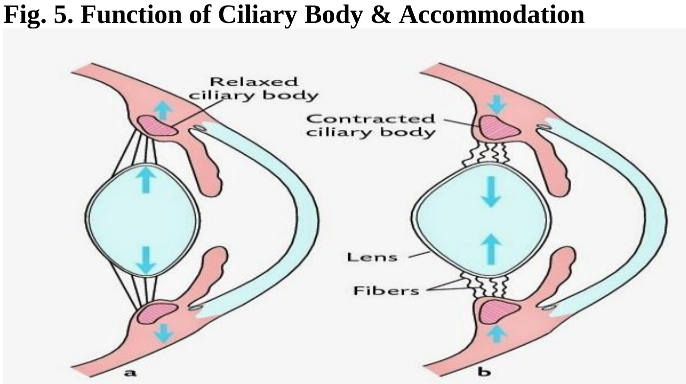

Fig. 6. Myopic Vision Of An Eye

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Fig. 7. Hyperopic Vision of An Eye

Fig. 8. Myopia And Its Correction With Concave Lens

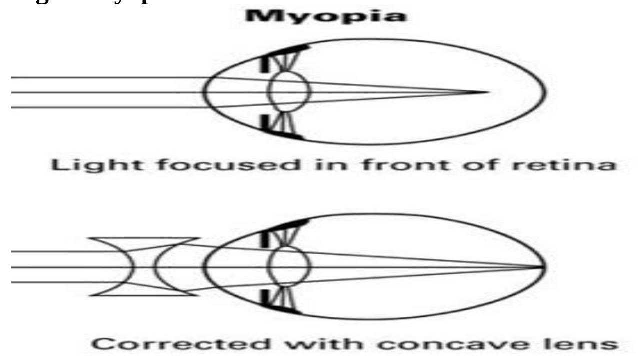


Fig. 9. Hyperopia And Its Correction With Convex Lens

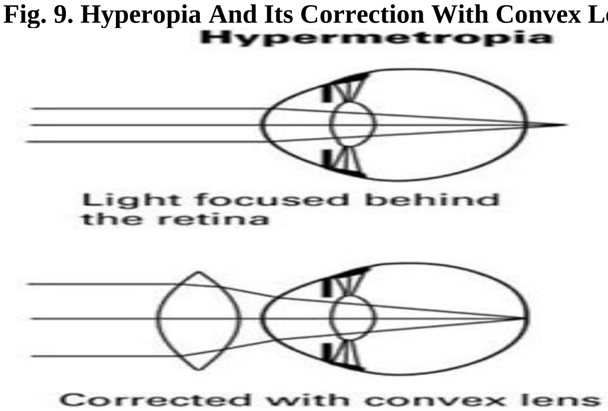
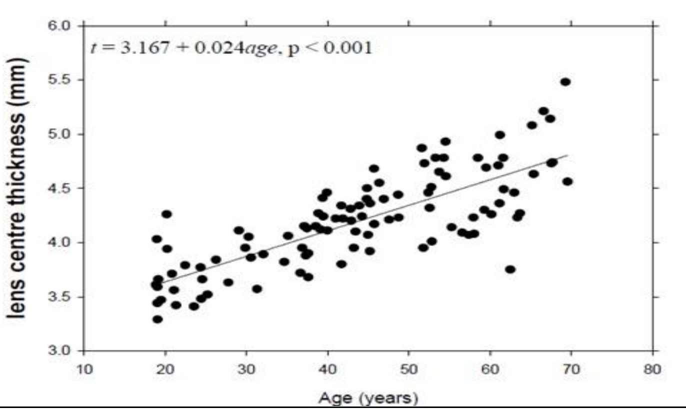


Fig. 10. Relation Between Age & Centre Thickness of The Lens/Radius of Curvature[8-9]



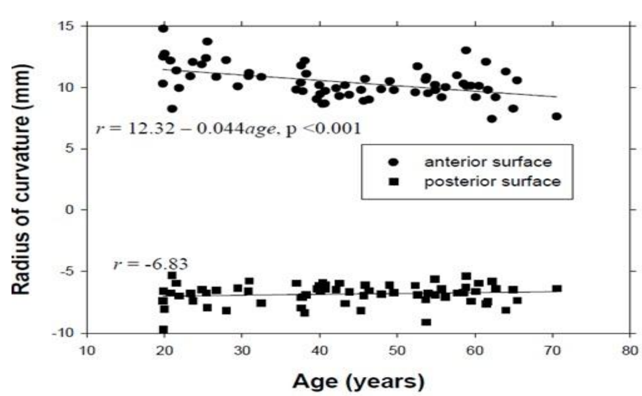


Fig. 11. Refractive Errors With Aging Eye [8-9]

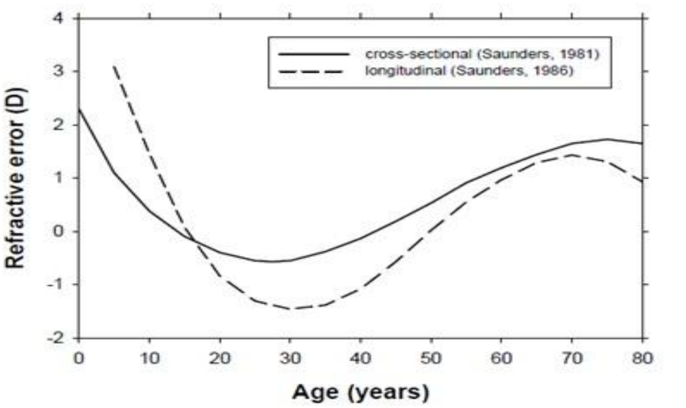


Fig. 12. Relation Between Age & Amplitude of Accommodation [8]

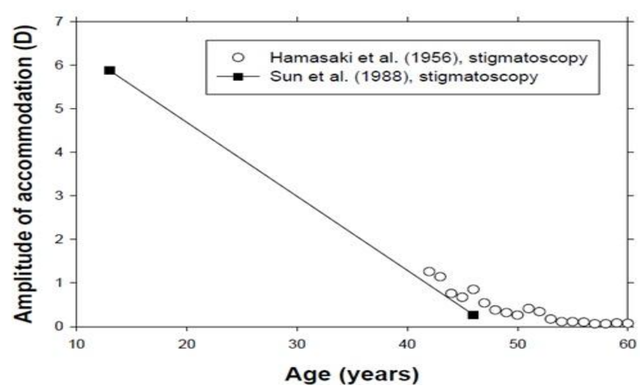


Fig. 13. Relation Between Age & Pupil Diameter [8]

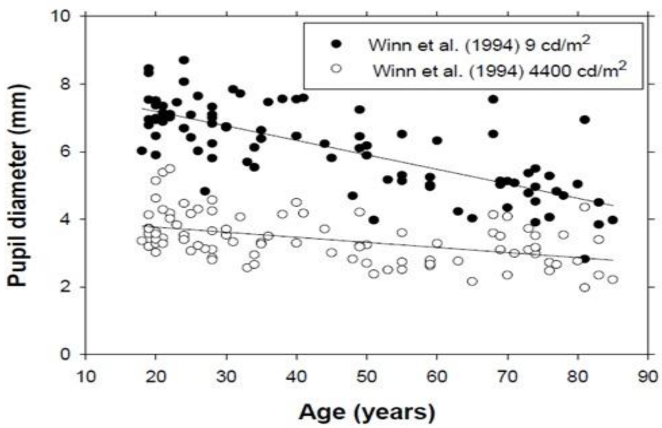


Fig. 14. Age & Equivalent refractive index of lens [9]

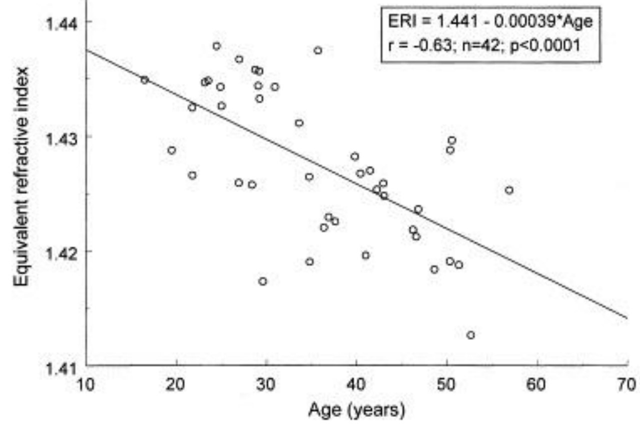


Fig. 15. Cataract In The Human Eye Lens [18]

Fig. 16. Photoreceptors/Rod & Cone Cells in Retina

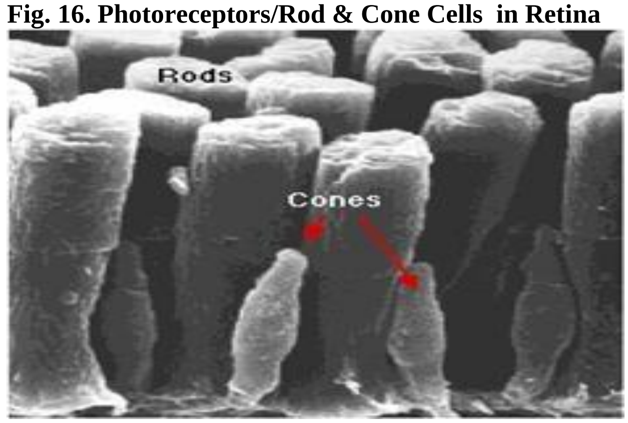
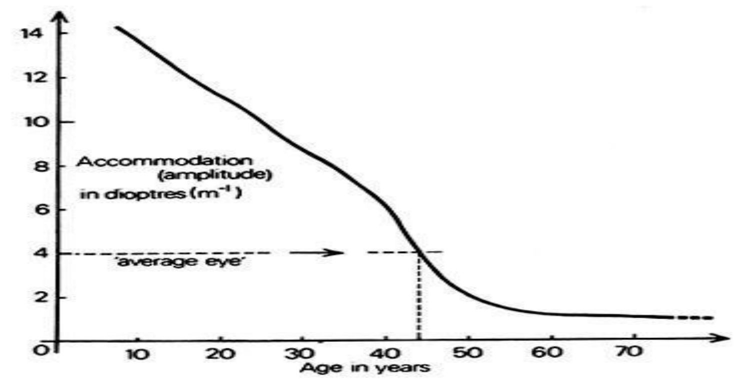


Fig. 17. Relation between age and near point/accommodation



CONCLUSION

The human eye is the most perfect and most beautiful organ amongst all the organs of the human body. It contains within itself all those structures which modify the light rays proceeding from the objects, according to the well-known laws of optical science. Many studies discussed in this paper support the fact that visual acuity impairs with the age [1-27]. It demands comprehensive eye care and immediate attention to identify and set the priorities to deal with visual impairment before it becomes a serious medical condition. Any distorted or blurred vision is a caution to visit the ophthalmologist or optometrist to seek his opinion. Laser surgery is another choice of treatment to correct the refractive errors. LASIK "laser-assisted in situ keratomileusis," is the most commonly performed laser eye surgery with 96% success rate. It is essentially required to improve the availability and awareness of eye-care services by establishing new vision centers and providing essential equipment for screening, treatment and training.

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