

What happens when light meets matter? There is always an interaction: light is scattered at a wall's surface, reflected off a surface of water, partially absorbed and partially reflected by a green leaf, refracted when it enters glass, and excites chemical processes in retinal rods and cones, even at very low intensities. The details depend on the structure of the matter and on the wavelength of the light. Additional phenomena are refraction, diffraction, and fluorescence – even the miracle of transparency is fascinating. How is it possible that light passes almost completely unimpeded through a structure like the cornea or through water molecules? In this chapter, we discuss how light is affected by matter. In Chap. 7, we will discuss the special action of light on tissues.

2.1 Phenomenology

Almost all of the processes mentioned above can be illustrated using the eye as an example. Thanks to the refraction of light at the air–corneal interface and at the aqueous humor–lens interfaces, a sharp image is engendered on the retina. The cornea reflects a crossbar or a Placido disk. The aged lens scatters light and reduces the image contrast at the level of the retina. Blood mainly absorbs blue and green light and converts the energy into heat so that red is the dominant color in the light that is scattered back.

The blue iris owes its color to the same process that produces a blue sky: i.e., light scattered by particles that are smaller than the light wavelength.

Shorter wavelengths are scattered much more than the longer ones (Rayleigh scattering). The color of a brown iris arises from absorption by a pigment. The white color of the sclera is explained by the almost total scattering of all colors in every direction. In fluorescence angiography, the conversion of light to longer wavelengths is applied. Due to its wave properties, even the diffraction of light is manifest within the eye: the smaller the pupil is, the larger the smallest image of a point source of light at the retina will be. A few of the more important processes are depicted in Figs. 2.1 and 2.2. In the following chapters, we discuss in detail some of these processes and their ocular manifestations.

2.2 Fundamental Physical Processes

We shall occupy ourselves only briefly with the atomic bases of the mentioned processes. The basic principle is always the same with visible, ultraviolet, or infrared light. When light encounters a surface or passes through a medium, inevitable interaction occurs between the light and the electrons of the atoms and molecules of the material. A simplified picture of classical electrodynamics involves the interaction of two fundamental processes: first, the light exerts a force on the electron¹ and, second, as a charged

¹More precisely, the charged electron experiences an accelerating force in the light's electric field.

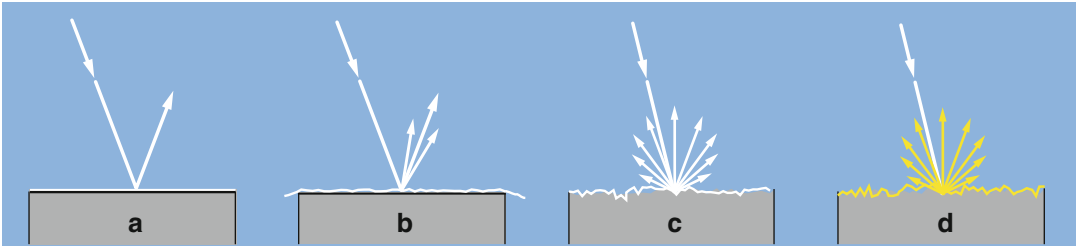


Fig. 2.1 Some of the interactions of white light with surfaces. (a) Specular reflection at a smooth surface. (b) Lustrous reflection from paper with a slightly rough sur-

face. (c) Diffuse reflection from a whitewashed wall; no absorption. (d) Diffuse reflection with absorption of the shorter wavelengths at a painted yellow wall

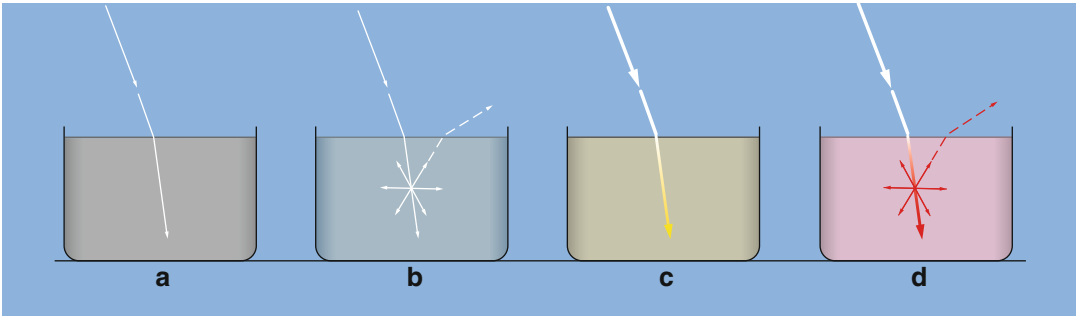


Fig. 2.2 Some interactions of white light with media. Refraction takes place when a ray of light penetrates from above into the medium below (as seen in these diagrams). The media are, for example, gases, fluids, or tissues. (a) Refraction. In the denser (lower) medium, light travels more slowly and in a changed direction. (b) Scattering,

not color-selective (strongly diluted milk). (c) Absorption without scattering (clear medium). After blue has been absorbed, the remaining ray of light is yellow. (d) Absorption of blue and green, additional scattering of the light (cloudy medium such as blood)

particle, the accelerated electron radiates electromagnetic waves (light).

Scattering of light by a free electron provides an example. When light meets an electron, it is “shaken” at the frequency of the light. As a result, the electron sends out light with the same frequency in any direction. Thus, light scattering takes place. This process represents one of the impediments that solar photons surmount when they must fight their way from where they are produced in the interior of the sun to its outer surface. A second example is that light penetrating through a metallic surface causes the cloud of negative charge – consisting of weakly bound electrons of the metal atoms – to vibrate in phase with the light frequency. This vibrating and charged cloud then produces light of the same frequency, specifically reflected light. A third example is that, inside glass, electrons are also stimulated to vibrate. Instead of reflection, the

only consequence in glass is that the light is slowed down somewhat without being absorbed. This slowing down of the light is the basis for refraction (Sect. 2.4).

The electric field of light exerts forces of the same strength on the protons of the atomic nuclei as it does on the electrons. However, due to the much larger mass of the protons and their strong binding within the atom’s nucleus, the interaction of visible light with the nucleus is far weaker and is practically negligible in the visible range.

The basic process of the interaction of light with matter can be described more precisely by means of quantum theory: the electron of an atom, a molecule, or an atomic lattice can absorb a photon and use its energy to jump into an energetically higher state (Fig. 2.3). Conversely, an electron can fall into a state of lower energy, with the energy difference being sent out as a photon (Fig. 2.4). Actually, it is usually not just a single electron but,

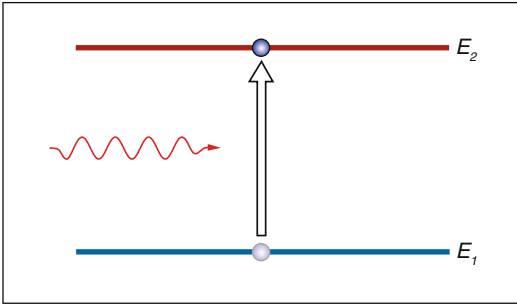


Fig. 2.3 Absorption of a photon. Its energy is transferred to the atom and raises its electron shell onto a higher energetic state. This process is only possible when the photon's energy "fits" a gap in the atom's energy spectrum

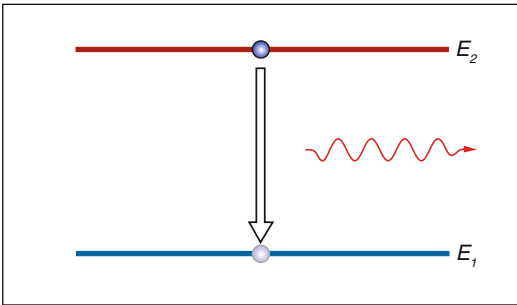


Fig. 2.4 Spontaneous emission of a photon by an excited atom or molecule. Typically, this process occurs spontaneously, often only a few nanoseconds after the absorption of energy. The energy difference between the two atomic states determines the frequency (and, thus, the wavelength) of the departing photon. The direction of flight of the emitted photon is random

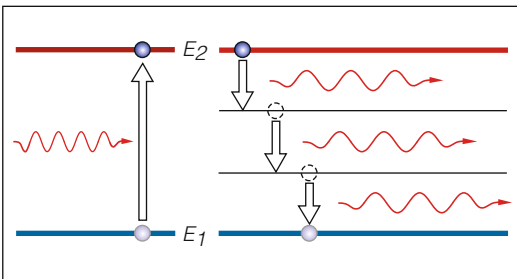


Fig. 2.5 Absorption of a photon and dispersion of the energy into lattice vibrations. The absorbed light energy warms the absorber

rather, the whole shell of an atom or molecule that experiences a change of state in these processes. Besides these two basic processes (absorption and emission), there is a third one: stimulated emission. This will be treated in Sect. 3.4.

Scattering and absorption fit quite simply into this picture of elementary processes. Scattering means that a photon is absorbed and immediately emitted again. The absorbed energy equals the emitted energy and, as a result, it does not change the wavelength of the light. The absorption of light by a black piece of paper or by the pigments of a brown iris follows another scheme: first, the absorption of a photon results in the transition of an atom or molecule to a state of higher energy. This energy is now converted in small portions into vibrations of the material. Heat is generated from the photon's energy (Fig. 2.5). Which one of the aforementioned processes takes place depends on the material, more precisely on its structure and molecular composition.

2.3 Transparency

Keeping in mind that light is scattered when it encounters an obstacle, the existence of transparent media such as glass, water, corneas, crystalline lenses, and air seems quite miraculous. Inside these media, interactions between the light and the materials still occur, but it only leads to the light's traveling more slowly than it would in a vacuum.² This slowing down is quantified as the refractive index n : the velocity of light in the medium amounts to $c' = c/n$, where c is the velocity of light in vacuum ($c \approx 300,000$ km/s). For example, in water, light travels with a velocity of $c' \approx 225,000$ km/s ($n = 1.33$).

Pure water is a classic example of an almost completely transparent medium for visible light. An eye exhibits several portions of tissue that are more or less transparent, such as the cornea, crystalline lens, aqueous humor, and the vitreous body, as well as the inner layers of the retina. A medium is always transparent only to a certain

²Why never faster? This is difficult to understand intuitively but follows from Maxwell's electrodynamic equations. The slowing down is the product of a consistent interplay between the electric and magnetic fields of the penetrating light, the vibrations of the electron cloud, and the light generated by these vibrations.



Fig. 2.6 Multi-layer construction of the cornea (Courtesy of E. van der Zypen, University of Bern)

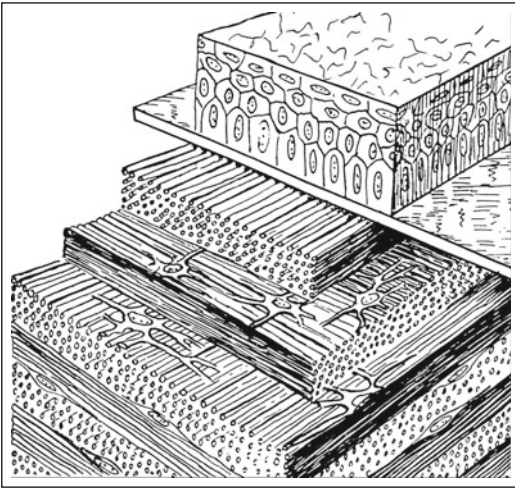


Fig. 2.7 Multi-layer construction of the cornea (Courtesy of H. Elias and J. E. Pauly (1966) *Human Microanatomy*. F.A. Davis Comp., Philadelphia. With permission)

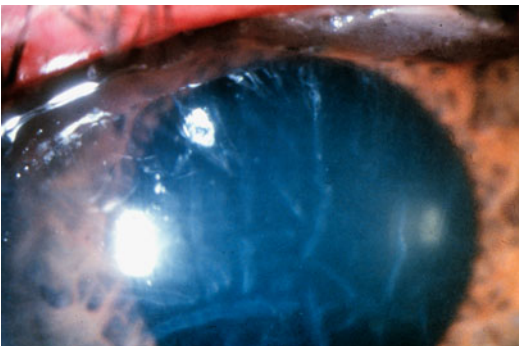


Fig. 2.8 Reduced corneal transparency due to swelling of the stroma

part of the electromagnetic spectrum. For example, water is opaque to radiation in the infrared range (see Sect. 2.8), while the cornea blocks radiation in the ultraviolet range.

It is impressive how nature has been able to construct transparent tissues. The cornea is made up of multiple layers (Figs. 2.6 and 2.7). The largest portion consists of the so-called stroma, which contains relatively few cells but many collagen fibers. For the stroma to be transparent and remain so, a very special arrangement of these collagen fibers must be maintained. The fibers are packed tightly and run from limbus to limbus. The cornea is transparent only as long as the separation between the collagen fibers is less than half a wavelength of the light that passes through. If too much water is present in the stroma (for example, when the pump function of the endothelium fails), the collagen fiber separation increases and the cornea loses its transparency (Fig. 2.8). This can occur, e.g., in cases of corneal decompensation. Here, we have a situation where the incorporation of clear, transparent water leads to clouding of the corneal medium.

The crystalline lens of a healthy person is also transparent. It consists of the capsule, the epithelium, and the lens fibers. The lens fibers run in a meridional fashion from the posterior to the anterior poles (Fig. 2.9). Again, the regular arrangement of these fibers is a prerequisite for the transparency of the lens.

The retina is also transparent, so light can reach the cones and rods unimpeded (Fig. 2.10). However, it can also lose its transparency through water retention (retinal edema). A similar phenomenon can occur at the optic nerve head. The nerve fiber layer continues from the retina into the optic nerve head. The nerve fiber layer is transparent, so, in ophthalmoscopy, the ophthalmologist sees through this layer to deeper layers and, thereby, sees the clear, sharp boundaries of the retina, pigment epithelium, and choroid (Figs. 2.11 and 2.12). The optically sharp delimitation of the optic nerve head is, thus, conditioned by deeper layers. If the nerve fiber layer loses its transparency, either partially or totally, the optic nerve head's boundaries appear blurred. This loss

Fig. 2.9 Regular ordering of the lens fibers. *Right:* Scanning electron micrograph showing the orderly arrangement of hexagonal lens fibers. (*Right figure from Adler's Physiology of the Eye* (2003) Mosby. With permission. Courtesy of J. Kuszak)

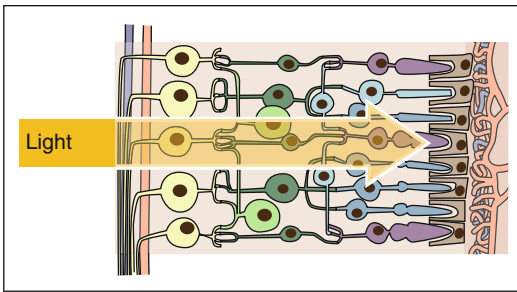
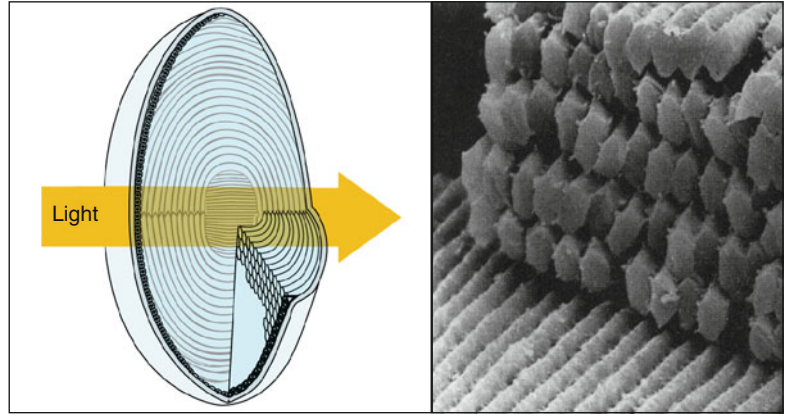


Fig. 2.10 Transparency of the retina



Fig. 2.12 Sharply defined retina, pigment epithelium, and choroid

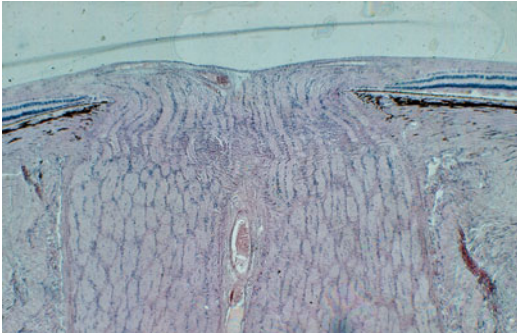


Fig. 2.11 Both the choroid and the pigment epithelium end sharply at the border of the optic nerve head, whereas the superficial nerve fiber layer is continuous (Courtesy of P. Meyer, University of Basel)

of nerve fiber transparency is encountered, for example, in cases of papilloedema in which the axons swell and thereby lose their transparency (Fig. 2.13).



Fig. 2.13 In the case of papilloedema, the nerve fibers lose their transparency. This gives the impression of a blurred-bordered optic nerve head

2.4 Refraction

If a beam of light meets a smooth interface between two transparent media that have different refractive indices, both reflection and refraction occur (Fig. 2.14). The reflection is symmetric with respect to the surface normal,³ and the percentage of the light reflected increases with an increasing angle α . In Sect. 2.5, we will discuss reflection in more detail. The refraction of light is the basis for the optical imaging through the cornea, crystalline lens, eyeglasses, and optical instruments (e.g., magnifying glasses, microscopes, and refractive telescopes).

2.4.1 The Law of Refraction

The incident ray of light onto a surface, the refracted and reflected rays, and the surface normal all lie in the same plane (Fig. 2.14). The amount of light refracted depends on the ratio of the refractive indices of the two media. The relationship between the two angles α and β is specified by the law of refraction (Fig. 2.14). Depending on which culture one comes from, it

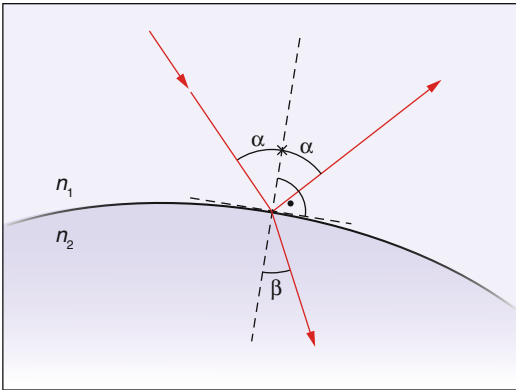


Fig. 2.14 Refraction at the interface of two media. The primary ray is partially reflected and partially refracted. α and β are the angles of the rays with respect to the surface normal. The law of refraction determines the angle β when α and the refractive indices n_1 and n_2 are given: $\sin \alpha / \sin \beta = n_2 / n_1$

³The surface normal is perpendicular to the surface.

is ascribed to either Snell⁴ or Descartes,⁵ both of whom rediscovered it at roughly the same time.⁶

Refraction is a consequence of the differing speeds of light in two media (Fig. 2.15). To understand this, we first note that the frequency of the light vibrations remains the same in both media (the vibrations on both sides of the interface are in step). Therefore, inside the medium with the slower light speed, the wavelength is smaller since the light moves one wavelength further during one period. Figure 2.15 shows that the continuous transition at the interface is possible only with a change in direction.

Lenses that are thinner in the center are called diverging lenses (“minus lenses”). Their optical powers are given as negative values. Lenses that are thicker in the center than the periphery are called collecting lenses (“plus lenses”). They bundle parallel light into a focus. The reciprocal value of the focal length (in meters) is called the optical

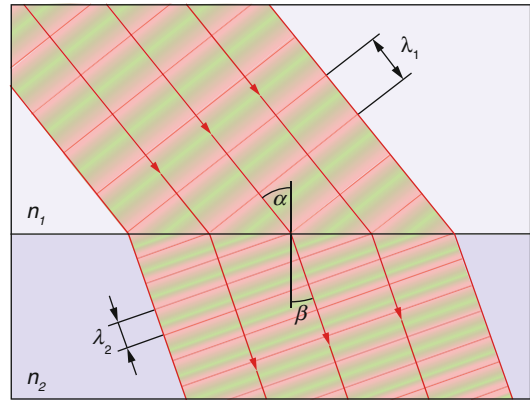


Fig. 2.15 Wave image of refraction. The differing light speeds in the two media give rise to differing wavelengths. The continuous transition of the phases at the interface is possible only with a change in direction. In a medium with an index of refraction n , the wavelength is n times shorter than in a vacuum. $\lambda_1 / \lambda_2 = n_2 / n_1$

⁴Willebrord van Roijen Snell (1580–1626), Dutch astronomer and mathematician.

⁵René Descartes, mentioned in Chap. 1.

⁶The earliest known discoverer was Ibn Sahl (940–1000), Persian mathematician and physicist in Baghdad. In 984, he wrote a tract concerning magnifying mirrors and glasses.

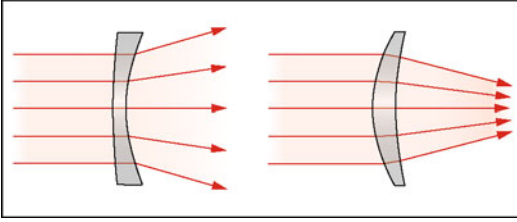


Fig. 2.16 *Left:* diverging lenses are thinner in the middle than on the edge. *Right:* collecting lenses are thicker in the middle than on the edge. Bending a lens inward or outward has little influence on its optical power

power and is measured in diopters, D (to give an example, a focal length of 0.25 m corresponds to a refractive power of 4 D). Bending a lens inward or outward slightly does not influence its refractive power (Fig. 2.16).

2.4.2 Dispersion

The refractive index of a transparent medium is slightly dependent on the wavelength and increases with shorter wavelengths.⁷ This gives rise to dispersion during refraction, i.e., to a breaking up of white light into various colors, as we mainly know from prisms or crystals (Fig. 2.17). The colors of the rainbow are also based on the dispersion in water droplets. In imaging systems, the corresponding color error is referred to as “chromatic aberration,” which can be observed as colored edges toward the periphery of the field of view of some binoculars. The error occurs because the lens edges split up the light into its spectral components like a prism. In other words, a simple lens has a slightly different focal length for each color (Fig. 2.18). Since the light that passes through the edges of the lens contributes most to aberration, this error is minimized with aperture stops. The basic idea for correcting color errors in imaging systems is outlined in Sect. 19.2.

Newton was interested in the chromatic aberration of the human eye. Its focal plane for blue light lies approximately 1 mm in front of that for red light. It is amazing that we perceive the chro-

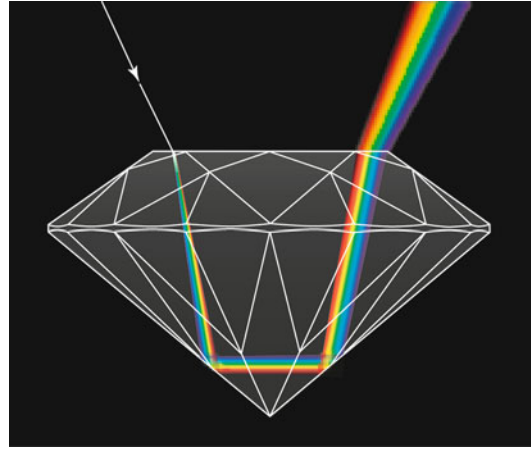


Fig. 2.17 Dispersion in a diamond. The refraction depends on the color: blue light is more strongly refracted than red light (exaggerated in the figure)

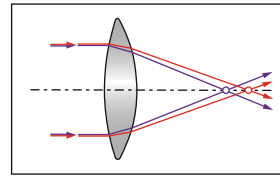


Fig. 2.18 Chromatic aberration in a simple lens: the focal length for blue light is shorter than for red light

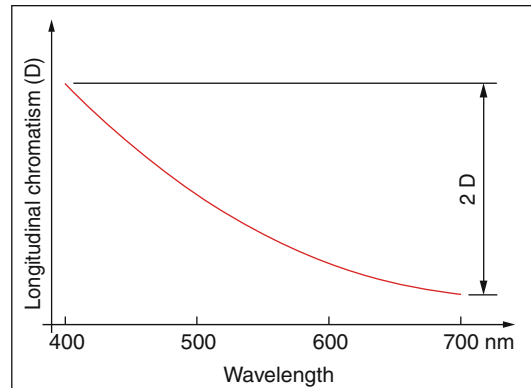


Fig. 2.19 The refractive power of the human eye depends on the color of the light. *Abcissa:* wavelength. *Ordinate:* variations of the refractive power. The total refractive power of the eye amounts to ca. 58 D

matic error of our eyes only under rare conditions, even though the difference between the refractive power for red and blue light amounts to ca. 1.5 D (Fig. 2.19). One reason could be that the innermost

⁷From 700 to 400 nm, the refractive power of water increases by ~4 %.

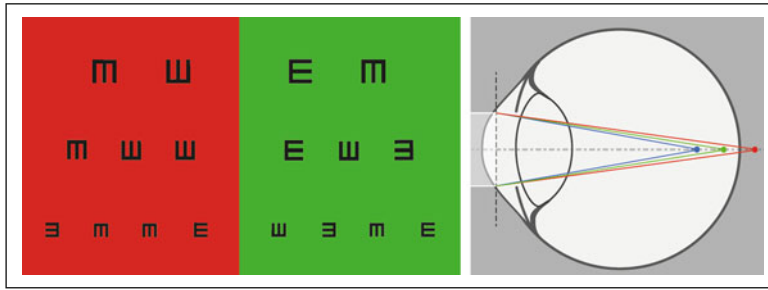


Fig. 2.20 Red-green balance of the refractive correction of an eye. *Left*: the correction is considered ideal when the symbols on the red and green backgrounds are seen to be equally sharp. *Right*: the red focus lies, then, just behind

the retina and the green one just in front. The distance of the blue, green, and red foci from the retina is exaggerated by a factor of 10. The distance between the red and green focus amounts to about 0.3 mm

part of the central visual field is insensitive to blue since the blue-sensitive rods are completely absent in a circular area of approximately 20 min of arc. We can make use of the eye's chromatic aberration in red-green balancing: a refractive correction is considered optimal when the edges of black letters are seen to be equally sharp against both red and green backgrounds. Green and red foci are, then, a little bit in front and a little bit behind the retina, respectively. When the perception on the red background seems sharper, the spectacle correction is slightly too much on the hyperopic ("plus") side (Fig. 2.20).

2.5 Specular Reflection

The oldest encounter of humans with the phenomenon of reflection is seen when looking at a quiet surface of water. Reflection occurs at every smooth interface between media of differing optical density, i.e., other refractive indices (Fig. 2.14). Reflecting surfaces can be smooth or uneven. A smooth surface yields specular reflections: we can see sharp images of the mirrored objects. An uneven surface, such as a painted wall, our skin, or normal paper, leads to diffuse reflections; we treat this in more detail in the following chapter. Reflection is also the reason that moist eyes are shiny (Fig. 2.22). Eyes that are not moist – for example, those of a deceased person – seem to be dull (Fig. 2.21).

The fraction of the light that is reflected depends on the angle of incidence, the ratio of the refractive

indices of the two media, as well as from the state of polarization of the incident light (see Sect. 1.6), but it does not depend on the color in most situations. For a perpendicular incidence from air to glass (or for a perpendicular exit out of glass into air), approximately 4 % of the light is reflected. For the transition from air to water, this is approximately 2 %. In a window with double-glazing, we see four reflected images of a candle flame.

A flat surface reflects an image that is true to scale. Spherical surfaces reflect objects either enlarged or reduced in size. Deviations from ideal forms are evident in the images they reflect. This can be used in diagnostics. If we observe the shape of a cross reflected by a cornea, we can draw conclusions about the shape of the corneal surface (Fig. 2.22). If, for example, a corneal erosion is present, the image of the cross will show a corresponding step. Modern keratometers that measure the corneal outer surface by processing a video recording of the reflected image of a pattern of concentric rings will be dealt with in Sect. 4.1.9.

So-called total internal reflection occurs when a ray of light tries to exit an interface into a

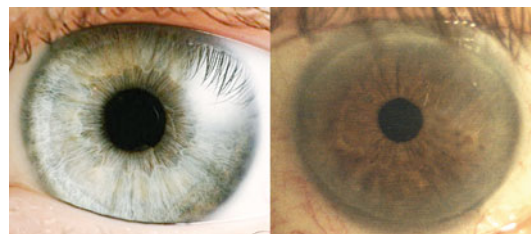


Fig. 2.21 *Left*: moist healthy eye. *Right*: dull eye of a patient with lagophthalmos

medium with a lower index of refraction and the angle of incidence with the surface normal exceeds a certain critical angle (Fig. 2.23). With total reflection, no light energy is lost. Light-conducting glass fibers – having cores with higher and claddings with lower refractive indices – transmit signals with large bandwidths over large distances. The light is “trapped” within the fiber (Fig. 2.24). Another application consists of image transmission via a fiber optic imaging cable that is constructed from a large number of individual fibers. An example is an endoscope (Fig. 2.25). Due to total reflection at the cornea, the anterior chamber angle cannot be observed directly. A contact lens is utilized to eliminate the total reflection of the cornea (Fig. 2.26).



Fig. 2.22 Specular reflection: the tear film covering the cornea reflects a crossbar

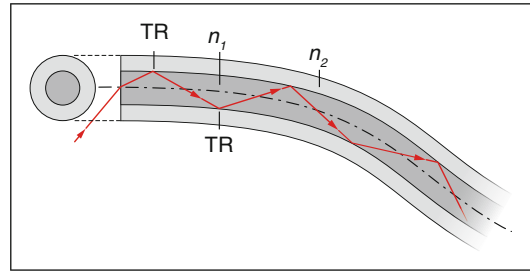
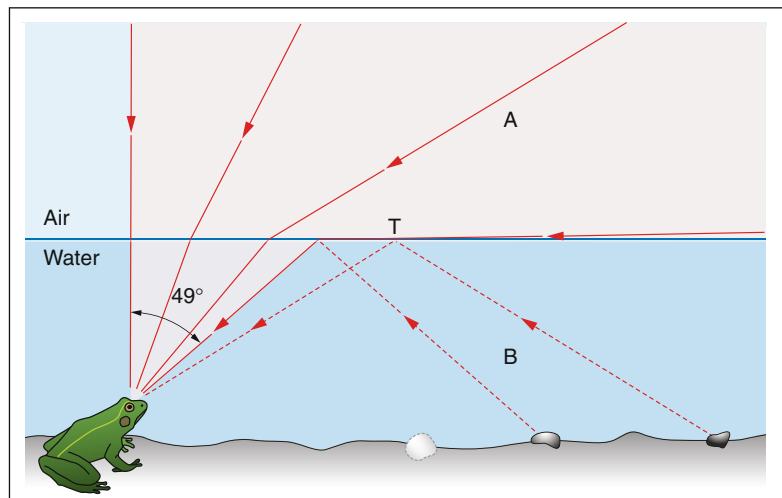


Fig. 2.24 Light conductor. The core has a higher index of refraction (n_1) than the cladding (n_2). The light travels along the core and, due to total reflection (TR), it cannot leave it



Fig. 2.25 Rastered imaging through an image-conducting fiber optic cable. Each fiber produces a point of light. The diameter of the fibers limits the resolution. This principle is applied in the endoscope

Fig. 2.23 Total reflection. In a part of its visual field, the frog sees a mirror image of the pond bottom (B) and, in another part, the outer world (A). For the transition from water into air (or vacuum) the critical angle is 49° . In accordance with the law of refraction, it corresponds to an angle of 90° in the optically thinner medium (air)



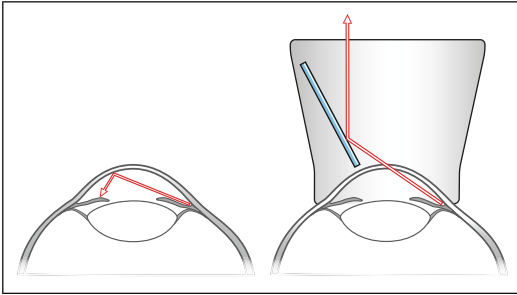


Fig. 2.26 Due to total reflection at the cornea–air interface (*left*), the anterior chamber angle is not visible without using a contact lens (*right*)

2.6 Diffuse Reflection at Surfaces

Rough surfaces, such as a piece of paper, reflect light back in all directions. This also occurs when sunlight strikes the wall of a house or the green leaf of a plant. Thanks to the diffuse character of the reflection, we see the illuminated object from every angle (Fig. 2.1c, d). This general picture will now be made more precise.

The most obvious is the phenomenon of the color of the reflecting surface. The wall of a house, being illuminated by the sun, appears white when its paint reflects all wavelengths of the incident light completely (Fig. 2.1c). The yellow color of a sunflower arises through the absorption of blue: together, the remaining green and red produce the perception of yellow. If a surface partially absorbs all the spectral portions of the light uniformly (50 % of it, for example), it appears to be gray, that is, without any color.

An example of a completely white surface is provided by snow. Its white color has a simple explanation: the tiny ice crystals reflect the light without any absorption. For the same reason, crystal sugar appears completely white. Strictly speaking, these phenomena are not surface effects; rather, the elementary processes with which a surface sends the incident light back occur in a three-dimensional boundary layer: the light always penetrates into the material and, in the case of paper, for example, is sent back out in a series of complex refractions, diffractions, and scatterings within the structure of the material. From the

transparency observed in very thin paper, we can recognize that the layer in which the aforementioned processes occur must have a certain thickness.

The directional distribution of diffusely reflected light can exhibit differing characteristics depending on the material and surface texture. An extreme case is the mirror that reflects the incident light in only one direction. The other extreme case is the so-called Lambertian reflector: it reflects the light in all directions, independent of the angle of incidence, such that a surface appears equally bright when viewed from any direction (Fig. 2.1c, d). Between these extremes is shiny paper that returns light mainly in a relatively narrow set of directions (Fig. 2.1b) or shiny surfaces that mirror a part of the light and diffusely reflect another part. A water surface, moved slightly by the wind, can exhibit both diffuse and specular reflections at the same time. An interesting phenomenon is that dry sand is bright, while wet sand is dark.

2.7 Light Scattering in Media

An outer surface does not always scatter back all the light that penetrates it. Instead, the scattering can also take place deeper inside the interior of the medium. Among innumerable examples, the blue of the sky is the most well known: the air molecules scatter sunlight and mainly the shorter wavelengths (Fig. 2.27). Without the scattering, the sky would appear black to our eyes and light would come into our eyes only when looking directly at the sun (Fig. 2.28). Other examples include, say, the visibility of a laser beam from the side when it passes through smoke or strongly diluted milk. A glass of beer absorbs light of short wavelengths and scatters light with longer wavelengths in all directions.

The pure white color of clouds can be explained by the fact that the reflection and refraction of the light in water droplets happens with almost no absorption. The gray or black

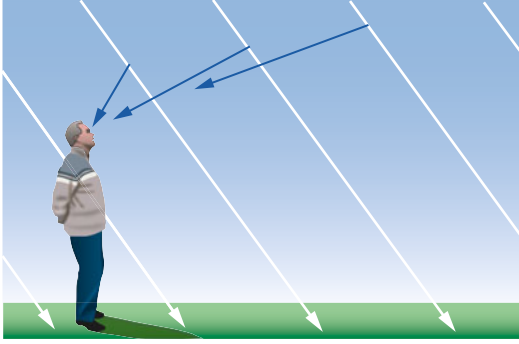


Fig. 2.27 The observer sees a blue sky because the atmosphere's molecules scatter the blue wavelengths of sunlight more than the red ones



Fig. 2.28 The astronauts on the moon saw the earth against a black sky (Courtesy of NASA)

appearance of heavy clouds derives from the fact that the light coming from above is mainly scattered and reflected back upward, while only a small part passes through.

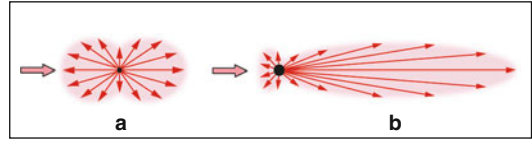


Fig. 2.29 Angular distribution of the scattered light. (a) Scattering due to particles with diameters far below the light wavelength (Rayleigh scattering). (b) Scattering due to particle diameters of a few light wavelengths (Mie scattering). Light arrives from the left. With large particles, the scattering takes place mainly in the forward direction

The scattering of light by particles depends on the particle size. The scattering due to particles that are considerably smaller than the light wavelength is known as Rayleigh scattering.⁸ The best known example is the scattering of sunlight by the molecules of the atmosphere. The blue portion of the sunlight is approximately six times more strongly scattered than the red portion (Fig. 2.27). Rayleigh scattering occurs in all directions. The blue iris with its missing pigmentation of the stroma represents a further example of Rayleigh scattering. It occurs due to scattering on structures of the iris that are considerably smaller than the light wavelength.

For larger particles, e.g. from atmospheric pollution, with diameters on the order of light wavelengths or larger, the scattering takes place mainly in the forward direction, and it is less color-dependent (Mie scattering,⁹ Fig. 2.29). The scattered light loses the blue dominance of the Rayleigh scattering and becomes increasingly whiter with the increasing diameter of the scattering particles. A nice manifestation of the forward direction of the scattering of sunlight on atmospheric particles is the whitish appearance of the sky near the sun: The scattering due to water droplets and atmospheric pollution (aerosols, salt

⁸John W. Strutt, Baron Rayleigh, 1842–1919. English physicist. Nobel Prize 1904.

⁹Gustav Mie, German physicist, 1868–1957.

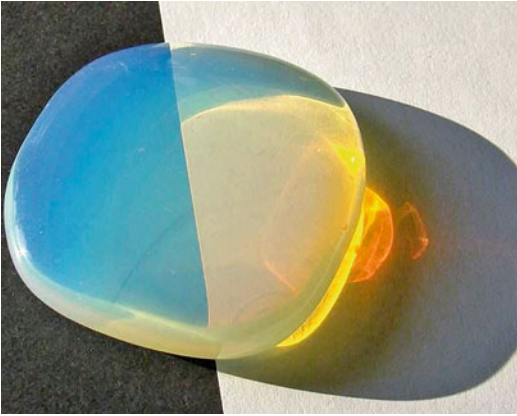


Fig. 2.30 Opal glass illuminated from the left. With a black background, it appears bluish (scattered light). The light that passes through it is orange-yellow because the blue light is partially scattered away. The black shadow appears to the right since no light arrives there due to refraction. (Courtesy of D. Zawischa, University of Hannover, <http://www.itp.uni-hannover.de/~zawischa/ITP/streuung.html#tyndalleffekt>)

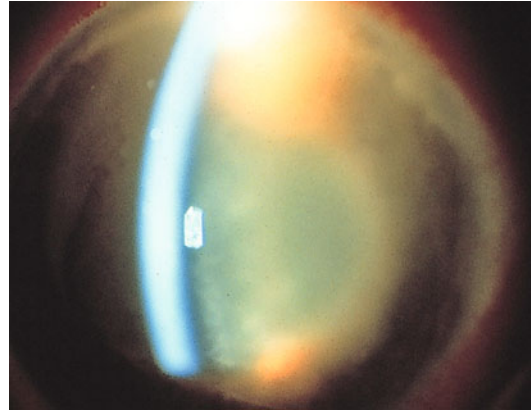


Fig. 2.31 Tyndall effect due to exudation of proteins

particles) often overpowers the blue Rayleigh scattering.

Light scattering due to submicroscopic particles in an apparently homogenous medium is known as the Tyndall effect.¹⁰ An especially beautiful example – opal glass – is shown in Fig. 2.30. In ophthalmology, the glow caused by the incident slit lamp light, such as in the anterior chamber, is denoted as a positive Tyndall effect. It indicates that protein molecules are present in the aqueous humor and this, in turn, is a manifestation of a disturbed blood-aqueous barrier, mostly in connection with inflammation (Fig. 2.31).

The so-called transparent media of the eye are practically never fully transparent but scatter light to some extent. Observation of the cornea and lens with the slit lamp is based on the light scattered by these media¹¹ (Fig. 2.32). If a photograph of the anterior part of the eye is analyzed densitometrically, we can obtain a measure of the scattering, for example, of a cataract (Figs. 2.33

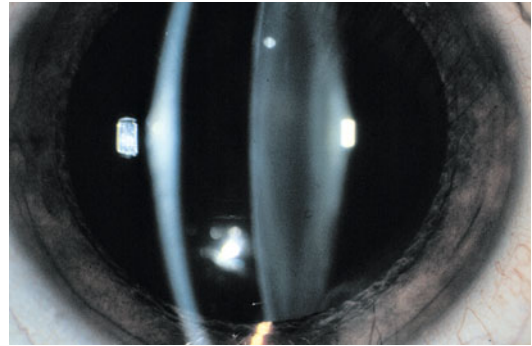


Fig. 2.32 Backscattered light from the cornea and lens as observed with the slit lamp

and 2.34). The forward scattered light disturbs patients, while the physician perceives only the light that is backscattered. Their ratio depends on the type of cataract. The visual impairment by light scattered by the lens is well known (Fig. 2.35).

¹⁰John Tyndall, Irish physicist, 1820–1893.

¹¹In photography of the anterior chamber, the Scheimpflug principle is frequently applied. In 1907, by tipping the image plane, Theodor Scheimpflug (Austrian naval officer and photographer, 1865–1911) was able to achieve sharply focused images of planes that were not perpendicular to the direction of view.

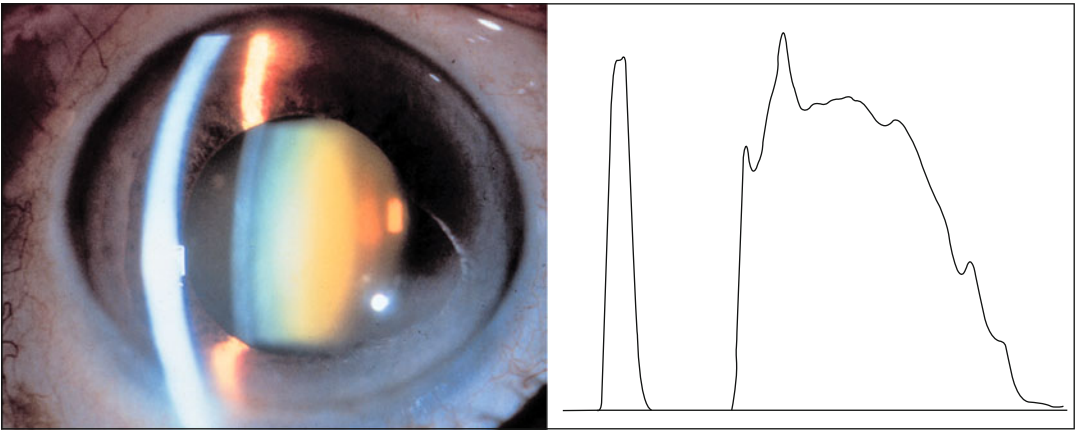


Fig. 2.33 Backscattered light from a nuclear cataract as seen with the slit lamp (*left*) and as shown in a densitometric profile (*right*)

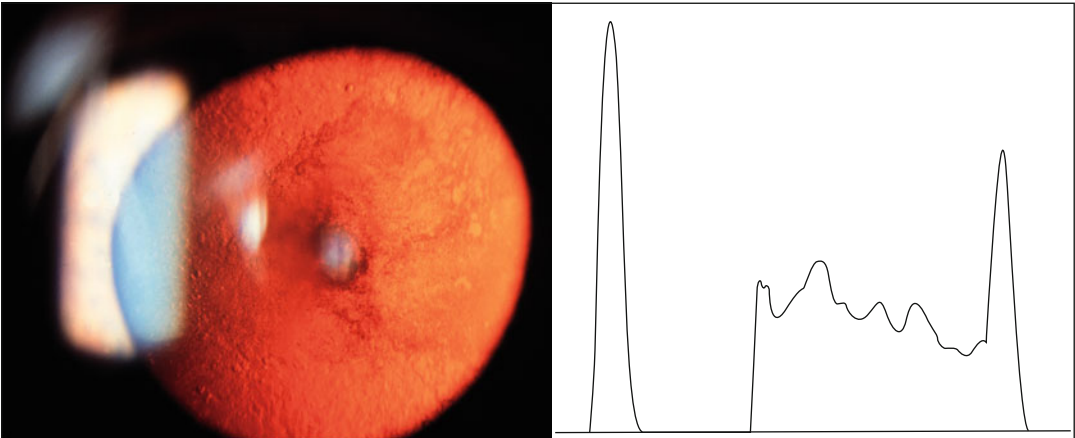


Fig. 2.34 A posterior subcapsular cataract produces more forward light scatter but only little backscatter. *Left*: observation with the slit lamp. *Right*: the corresponding densitometric profile (Note the difference between the profiles in Figs. 2.33 and 2.34)



Fig. 2.35 Simulation of light scatter caused by lens opacity

2.8 Absorption

Scattering at an exterior surface can be modified by the absorption of a portion of the incident light. A black surface swallows up all incident light. A piece of paper appears red when it absorbs the blue and green components of the light. If, for all colors, the same amount is absorbed, the surface appears gray. Absorption can also occur in the interior of a material and be also connected with light scattering. Red wine lets a part of white light pass through, absorbs the blue and green components, and scatters the red component sideways and back. In Sect. 1.5, we showed examples of body colors with their associated absorption spectra.

In the language of atomic physics, absorption takes place in the following way: the energy of the “swallowed” photon is transformed into the excitation energy of a cloud of electrons. Instead of this energy being re-emitted immediately as a single photon with the original energy, as occurs in a scattering process, it can be converted into vibrational energy of the material (i.e., heat) or into several energetically weaker infrared photons (Fig. 2.5).

Molecules that are intensively absorbing are called pigments. Through differing absorption spectra, brightness and color contrasts arise. We distinguish between inorganic and organic pigments. Inorganic pigments are crystals, polycrystalline powder, aggregates, and agglomerates. They come in the form of oils, lacquers, etc. They were used in cave paintings as early as 30,000 years ago (Fig. 2.36). Organic pigments are present in



Fig. 2.36 Cave painting

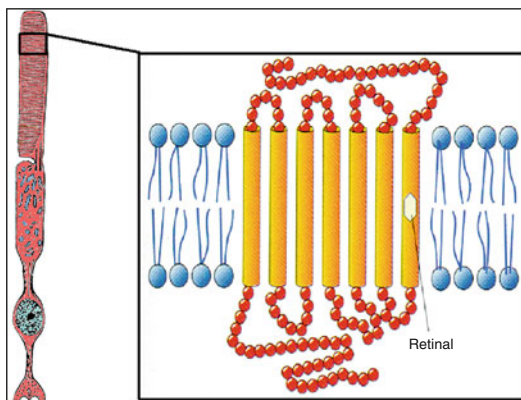


Fig. 2.37 Absorption of light by retinal. The same molecule (retinal) stands at the beginning of the cascade of processes leading from the arrival of a photon down to an electrical pulse in all three cones (red-, green-, and blue-sensitive). The differing sensitivity spectra go back to the embedding of cis-retinal in the protein opsin, the amino acid sequences of which differ slightly from those of the rods and also between the cone types. (From Flammer J (2006) *Glaucoma*. Hogrefe & Huber, Bern. With permission)

almost all creatures. Hemoglobin, for example, gives blood its red color, chlorophyll turns leaves green, etc. Organic pigments share many double bonds; i.e., they are multi-unsaturated. Thus, an electron cloud is formed that can absorb light.

Black and colored pigments are also applied in so-called xerography. The Greek word “xeros” means “dry.” In 1937, the printer Chester Carlson developed a printing process that does not require the use of liquid chemicals. Today, it is still the basic principle underlying laser printers and copy machines. In this process, a thermoplastic powder – the toner – is applied to locations that were not exposed to light on a roller; these are marked by differing photoelectric charges. The toner is then transferred onto the paper and the toner image is fixed to the paper with heat and pressure.

The absorption of light by chlorophyll is the basis for the energy acquisition of plants from sunlight. The absorption of light by the retinal molecule in our retina is the physical basis for vision (Fig. 2.37). The resulting conformation change of retinal leads to phototransduction in the retina. The retina is not completely transparent. Depending on the wavelength, light is more or less strongly absorbed in the differing layers.

This is important when regarding the photocoagulation of the retina (see Sect. 7.1).

The absorption of light by water or pigments strongly depends on wavelength (Fig. 2.38). For this reason, for the specific heating of certain ocular media, lasers with the correspondingly best-suited wavelength are utilized. For example,

wavelengths around 500 nm are especially suited for absorption by blood at the fundus of the eye. More information on this topic can be found in Chap. 7. Table 2.1 shows the absorption of light by water in the various parts of the spectrum.

2.9 Fluorescence

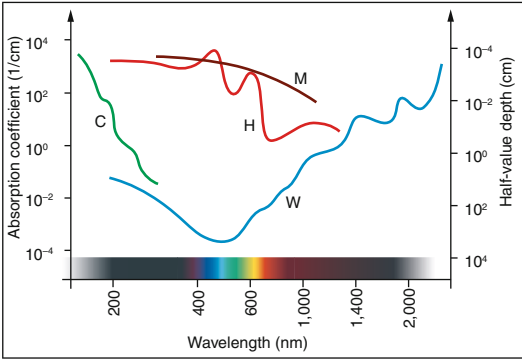


Fig. 2.38 Absorption coefficients of various materials. *W* water, *H* hemoglobin (in the physiological concentration of 150 g/l). *M* melanin, *C* collagen. *Left ordinate*: in units of cm^{-1} . *Right ordinate*: half is absorbed by the time it has traveled this far. Water is very transparent in the visual range and strongly absorbing in the infrared

Table 2.1 Absorption of light by pure water (approximate values for orientation). Half-value depth is the depth at which half of the light has been absorbed

Wavelength (nm)	Absorption coefficient (cm^{-1})	Half-value depth (cm)
200	0.08	10
500	0.0003	2,000
1,000	0.1	10
1,500	1	1
3,000	10,000	0.0001

In daylight, fluorescent materials are markedly bright. They are utilized, for example, in laundry detergents. This visual effect often originates from blue or UV light, which illuminates a material and, in turn, excites the emission of yellow or orange light to which our eyes are especially sensitive. The conversion always happens toward the longer wavelength and, thus, in the direction of decreasing photon energy because some energy is converted into molecular vibrations (heat). This behavior (absorption by short-wave light, emission of longer-wave light) is termed “fluorescence” (Fig. 2.39). The name stems from the mineral fluorite. This phenomenon can occur in organic materials and also in minerals. If we irradiate minerals with ultraviolet light, we can ascertain that individual mineral samples shine more or less brightly in various colors.

Fluorescent materials often produce light weakly. The emitted light is normally overwhelmed by the considerably more intense light of the illumination. For this reason, in both microscopy and ophthalmology, filters are employed. An initial filter verifies that, e.g., only blue light illuminates the object (excitation filter).

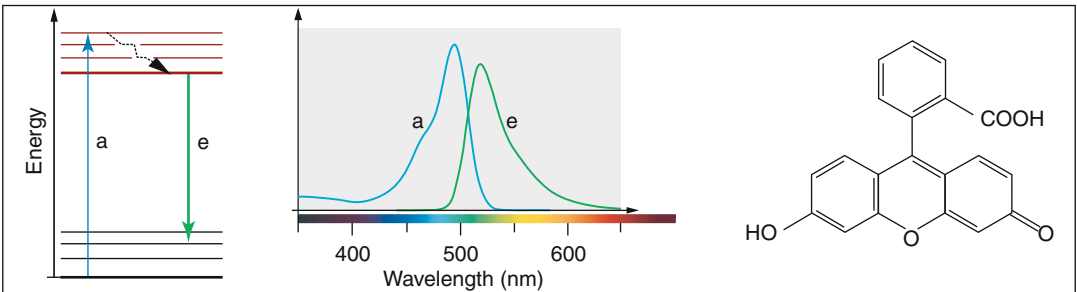


Fig. 2.39 Fluorescein. *Left*: term scheme. *Middle*: absorption spectrum (*a*) and emission spectrum (*e*). Absorption maximum at 485 nm, emission maximum at 514 nm. *Right*: formula of fluorescein

In the observation path, a second built-in filter, the so-called band stop filter, cancels out the excitation wavelength and lets only the fluorescent light through (e.g., green). In this way, the fluorescing molecules are markedly more visible than the rest of the specimen. In ophthalmology, fluorescein is mainly used, which leads to the emission of green light when stimulated with blue light (Fig. 2.40).

Fluorescence is also an important element in the so-called Goldmann tonometry (Fig. 2.41). In 1957, Goldmann,¹² at that time head of the Department of Ophthalmology of the University of Bern, described the principle of his applanation tonometry. A force that can be adjusted is transmitted to the measurement unit by means of a movable transfer arm mounted in a plane perpendicular to the eye. The force is adjusted so

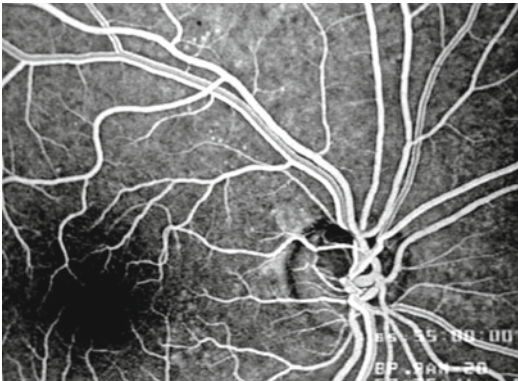


Fig. 2.40 An example of fluorescein angiography of a healthy eye

that a defined corneal area is flattened by the measurement unit's surface. A round adhesion meniscus forms in the tear film between the anterior surface of the tonometer unit ("tonometer tip") and the corneal epithelium. Thanks to previously instilled fluorescein, it is clearly visible in cobalt blue light (Fig. 2.42). Through a prism placed in the transparent measurement unit, the fluorescent fluid meniscus is divided horizontally into upper and lower half-rings. The prismatic shift corresponds to the diameter of the desired applanation. The pressing force of the tonometer tip is now increased until the insides of the half-rings just touch each other (Fig. 2.42). The surface area of the flattened cornea has now been attained and the intraocular pressure can be read according to the standards set by Goldmann (Fig. 2.43).

The fluorescein used in ophthalmology dissolves in the tear film but cannot diffuse through the lipophilic epithelium layer of the cornea. When an epithelial defect is present, the

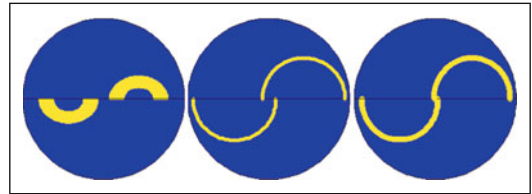
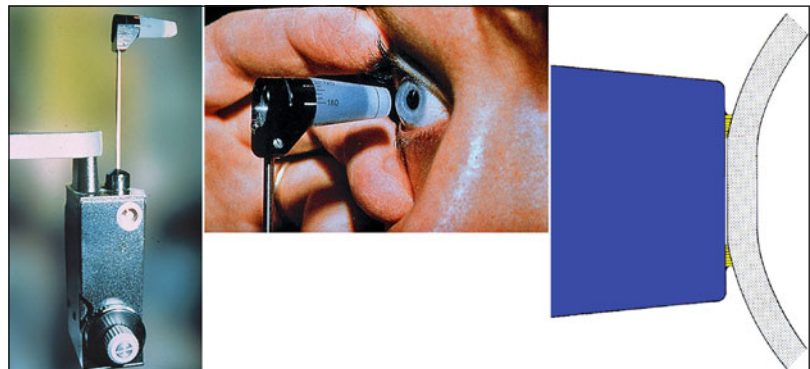


Fig. 2.42 Goldmann tonometry: *Left*: the applied force is too weak. *Middle*: it is excessive. *Right*: the force is correct for the desired applanation surface area

Fig. 2.41 *Left*: entire Goldmann tonometer. *Middle*: tip of the tonometer. *Right*: adhesion meniscus (yellow) around the applanated cornea



¹²Hans Goldmann (1899–1991). Swiss ophthalmologist. Famous for his applanation tonometer, contact lenses, perimeter, and contribution to the slit lamp.

fluorescein can diffuse into the hydrophilic corneal stroma (Fig. 2.44). At higher concentrations of fluorescein in the tear film, a small amount can diffuse into the anterior chamber even with an intact cornea. The temporal decay



Fig. 2.43 Hans Goldmann

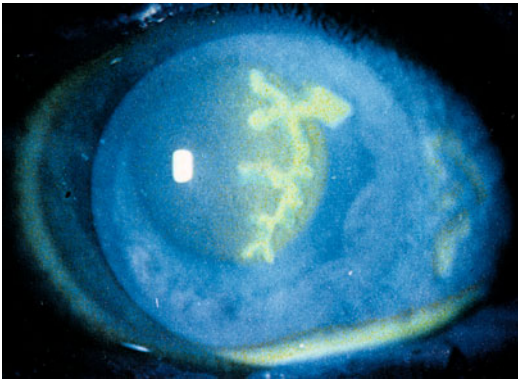


Fig. 2.44 Diffusion of fluorescein into the corneal stroma where the corneal epithelium is damaged by the herpes simplex virus

of the fluorescein concentration in the anterior chamber is measured in the so-called fluorophotometry procedure to quantify the turnover of the aqueous humor.

Another fluorescent substance frequently used in ophthalmology is indocyanine green (Figs. 2.45 and 2.46). It is suitable as an indicator and has the property that it does not diffuse out of the capillaries when bound to proteins. Its absorption and fluorescence spectra lie in the infrared (maximum fluorescence at approximately 810 nm in water).

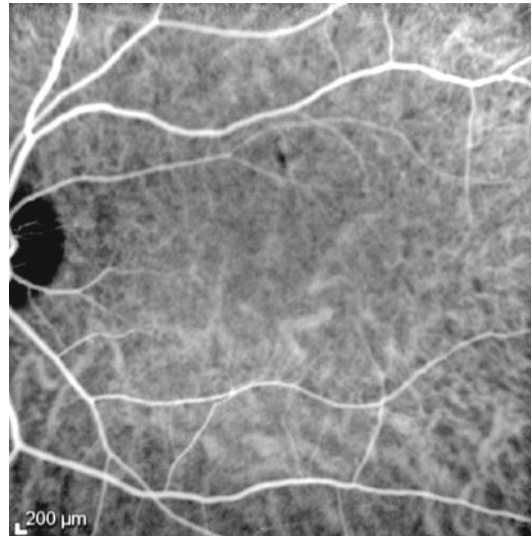


Fig. 2.46 Example of indocyanine green angiography. This patient suffers from a punctate inner choroidopathy

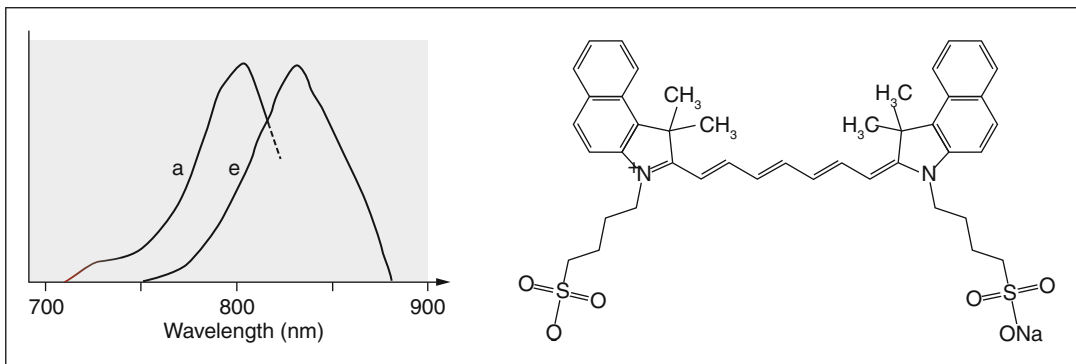


Fig. 2.45 Indocyanine green. *Left*: absorption (*a*) and fluorescence (*e*) spectra. *Right*: chemical formula



Fig. 2.47 Optic disc drusen. *Left*: regular fundus photo. *Right*: photo taken with appropriate filter to demonstrate autofluorescence

Many structures of the eye also show autofluorescence; i.e., they fluoresce without any fluorescent dye being applied. Examples include the optic nerve head drusen (Fig. 2.47) and the drusen of the retina. These can readily be seen clinically but even better in photos when the appropriate light filters are used. The crystalline lens also has a certain degree of autofluorescence. Changes in retinal autofluorescence are an early sign of retinopathy.

In some minerals, we can observe an additional property after the source of UV light has been turned off: they continue to glow for a few seconds, most often in a color other than the one they fluoresce in. This is called phosphorescence. In everyday life, using various time constants, this effect has found applications on the inside of monitor screens or for marking the ways to exits.

2.10 Diffraction

As mentioned earlier, all forms of waves, including light waves, are diffracted when they encounter an edge or pass through a narrow opening – like water waves when passing through the entrance to a harbor (Fig. 1.9). A

diffraction image can also be understood as an effect of interference among the entity of the waves that extend from all the points of the opening. Strictly speaking, diffraction is less the consequence of certain interactions between light and matter and more the expression of an inner property of light: its wave nature.

A curious phenomenon of diffraction was the object of controversy when the wave theory of light was being established. In 1818, Poisson¹³ pointed out that, as a consequence of the wave theory, a bright spot must appear in the center of a sphere's shadow because the waves originating from all the edges would arrive there in phase, irrespective of the position of the screen. To him, this seemed so absurd that he believed he had therefore disproved the wave theory. However, a short time afterward, “Poisson's spot” was actually observed and became one of the pillars supporting the wave theory of light (Fig. 2.48).

Diffraction has an influence on image formation in the eye. Even with a perfectly shaped cornea and lens, there is a limit to how small a

¹³Siméon D. Poisson, French mathematician (1781–1840).

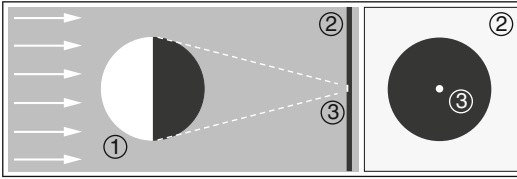


Fig. 2.48 Diffraction of light: Poisson's spot (3) on a screen (2) behind a sphere (1). The spot is observed at any distance behind the sphere

focal point parallel light can be focused on. It will always be a small disk rather than a spot: the so-called Airy disk. For a pupil of 2 mm,

the Airy disk at the retina has a diameter of about $12\text{ }\mu\text{m}$, corresponding to an angle of roughly 2 min of arc. For a pupil of 1 mm, the diffraction image at the retina is twice as large and reduces the visual acuity from 1.0 to 0.25 (from 6/6 to 6/24). We will return to the Airy disk in Sect. 19.1.

We can experience a nice demonstration of diffraction when looking through an opened umbrella or fine curtain material at a light source that is far away. The colored pattern we see is the result of the diffraction caused by the periodic structure of these textiles.

Basic Sciences in Ophthalmology

Physics and Chemistry

Flammer, J.; Mozaffarieh, M.; Bebie, H.

2013, XV, 250 p. 441 illus., 396 illus. in color.,

Hardcover

ISBN: 978-3-642-32260-0