Laser- Tissue Interaction
The interaction of radiation with matter.

Click on any type of radiation for more information.

Large number of available energy states, strongly absorbed.

Small number of available states, almost transparent.

Ionization energy

X-rays

Photoionization

Ultraviolet

Visible

Infrared

Molecular vibration

Microwaves

Molecular rotation and torsion

Compton Scattering

 Longer wavelength X-ray
Types of radiation

- ionizing radiation
- Non-ionizing radiation
You may click on any of the types of radiation for more detail about its particular type of interaction with matter. The different parts of the electromagnetic spectrum have very different effects upon interaction with matter. Starting with low frequency radio waves, the human body is quite transparent. (You can listen to your portable radio inside your home since the waves pass freely through the walls of your house and even through the person beside you!) As you move upward through you absorb more and more visible light to infrared and microwaves range, all the uv from the sun is ultraviolet strongly. In the lower absorbed in a thin outer layer of your skin. As you move further up into region of the spectrum, you become transparent again, x-ray the are gone. You then absorption because most of the mechanisms for absorb only a small fraction of the radiation, but that absorption involves the more violent ionization events. Each portion of the appropriate for the quantum energies electromagnetic spectrum has excitation of certain types of physical processes. The energy levels for all physical processes at the atomic and molecular levels are quantized, and if there are no available quantized energy levels with spacings which match the quantum energy of the incident radiation, to that radiation, and it will pass transparent then the material will be through

Electromagnetic spectrum annotated with physiological effects
Microwave Interactions

photons is in the range of microwave quantum energy. The quantum energy of microwaves is in the range of 0.00001 to 0.001 eV, which is in the range of energies separating the quantum states of molecular rotation and torsion. The interaction of microwaves with matter other than metallic conductors will be to rotate molecules and produce heat as a result of that molecular motion. Conductors will strongly absorb microwaves and any lower frequencies because they will cause electric currents which will heat the material. Most matter, including the human body, is largely transparent to microwaves. High intensity microwaves, as in a microwave oven where they pass back and forth through the food millions of times, will heat the material by producing molecular rotations and torsions. Since the quantum energies are a million times lower than those of x-rays, they cannot produce ionization and the characteristic types of radiation damage associated with ionizing radiation.
Small number of available states, almost transparent.
**Infrared**

The term "infrared" refers to a broad range of frequencies, beginning at the top end of those frequencies used for communication and extending up the low frequency (red) end of the visible spectrum. The wavelength range is from about 1 millimeter down to 750 nm. The range adjacent to the visible spectrum is called the "near infrared" and the longer wavelength part is called "far infrared.

In **interactions with matter** infrared primarily acts to set molecules into vibration. Infrared spectrometers are widely used to study the **vibrational spectra** of molecules.

- Frequencies: .003 - 4 x 10^4 Hz
- Wavelengths: 1 mm - 750 nm
- Quantum energies: 0.0012 - 1.65 eV
Infrared Interactions

The quantum energy of infrared photons is in the range 0.001 to 1.7 eV which is in the range of energies separating the quantum states of molecular vibrations. Infrared is absorbed more strongly than microwaves, but less strongly than visible light. The result of infrared absorption is heating of the tissue since it increases molecular vibrational activity. Infrared radiation does penetrate the skin further than visible light and can thus be used for photographic imaging of subcutaneous blood vessels.
Higher density of energy levels than in the microwave range, more strongly absorbed.

Infrared radiation vibrates molecules
• **Visible Light**

The narrow visible part of the electromagnetic spectrum corresponds to the wavelengths near the maximum of the Sun's radiation curve. In interactions with matter, visible light primarily acts to set elevate electrons to higher energy levels.

• White light may be separated into its **spectral colors** by **dispersion** in a **prism**

<table>
<thead>
<tr>
<th>Radio</th>
<th>Far IR, Microwave</th>
<th>IR</th>
<th>UV</th>
<th>x-ray</th>
<th>γ-ray</th>
</tr>
</thead>
</table>

- Frequencies: $4 - 7.5 \times 10^7$ Hz
- Wavelengths: 700-400 nm
- Quantum energies: 1.65 - 3.1 eV
• **Visible Light Interactions**

• The primary mechanism for the absorption of visible light photons is the elevation of electrons to higher energy levels. There are many available states, so visible light is absorbed strongly. With a strong light source, red light can be transmitted through the hand or a fold of skin, showing that the red end of the spectrum is not absorbed as strongly as the violet end.
Large number of available energy states, strongly absorbed.

Ionization energy

Visible light causes electron transitions

Electron level changes.
• While exposure to visible light causes heating, it does not cause ionization with its risks. You may be heated by the sun through a car windshield, but you will not be sunburned - that is an effect of the higher frequency uv part of sunlight which is blocked by the glass of the windshield.
• **Ultraviolet**

• The region just below the visible in wavelength is called the near ultraviolet. It is absorbed very strongly by most solid substances, and even absorbed appreciably by air. The shorter wavelengths reach the ionization energy for many molecules, so the far ultraviolet has some of the dangers attendant to other ionizing radiation. The tissue effects of ultraviolet include sunburn, but can have some therapeutic effects as well. The sun is a strong source of ultraviolet radiation, but atmospheric absorption eliminates most of the shorter wavelengths. The eyes are quite susceptible to damage from ultraviolet radiation. Welders must wear protective eye shields because of the uv content of welding arcs can inflame the eyes. Snow-blindness is another example of uv inflamation; the snow reflects uv while most other substances absorb it strongly.

• Frequencies: $7.5 \times 10^7 - 10^9$ Hz
• Wavelengths: 400 nm - 10 nm
• Quantum energies: 3.1 - 124 eV
Ultraviolet Interactions
UV photons above the ionization energy can disrupt atoms and molecules.

Large number of available energy states, strongly absorbed.

UV photons below the ionization energy are strongly absorbed in producing electron transitions.
The near ultraviolet is absorbed very strongly in the surface layer of the skin by electron transitions. As you go to higher energies, the ionization energies for many molecules are reached and the more dangerous photoionization processes take place. Sunburn is primarily an effect of uv, and ionization produces the risk of skin cancer.

The ozone layer in the upper atmosphere is important for human health because it absorbs most of the harmful ultraviolet radiation from the sun before it reaches the surface. The higher frequencies in the ultraviolet are ionizing radiation and can produce harmful physiological effects ranging from sunburn to skin cancer.

Health concerns for UV exposure are mostly for the range 290-330 nm in wavelength, the range called UVB. According to Scotto, et al, the most effective biological wavelength for producing skin burns is 297 nm. Their research indicates that the biological effects increase logarithmically within the UVB range, with 330 nm being only 0.1% as effective as 297 nm for biological effects. So it is clearly important to control exposure to UVB.
• **X-Rays**
  
  X-ray was the name given to the highly penetrating rays which emanated when high energy electrons struck a metal target. Within a short time of their discovery, they were being used in medical facilities to image broken bones. We now know that they are high frequency electromagnetic rays which are produced when the electrons are suddenly decelerated - these rays are called *bremsstrahlung radiation* or "braking radiation". X-rays are also produced when electrons make transitions between lower atomic energy levels in heavy elements. X-rays produced in this way have have definite energies just like other line spectra from atomic electrons. They are called *characteristic x-rays* since they have energies determined by the atomic energy levels.

  In **interactions with matter** x-rays are *ionizing radiation* and produce *physiological effects* which are not observed with any exposure of non-ionizing radiation, such as the risk of mutations or cancer in tissue.

  - Frequencies: $3 \times 10^2$ Hz upward
  - Wavelengths: 10 nm - > downward
  - Quantum energies: 124 eV -> upward
X-ray interactions

X-ray photon energies are far above the ionization energies of atoms.

Pair Production

Ionization energy
Since the **quantum energies** of x-ray photons are much too high to be absorbed in electron transitions between states for most atoms, they can interact with an electron only by knocking it completely out of the atom. That is, all x-rays are classified as **ionizing radiation**. This can occur by giving all of the energy to an electron (photoionization) or by giving part of the energy to the photon and the remainder to a lower energy photon (Compton scattering). At sufficiently high energies, the x-ray photon can create an **electron positron pair**.
Laser- Tissue Interaction

• Generally, laser radiation affects that kind of tissue, which absorbs the radiation. The absorption of laser radiation in tissue, especially in ocular tissue, is strongly wavelength dependent. The type of interaction depends on the wavelength and on the interaction duration.
Wavelength Considerations

- An overview of effects in the different wavelength ranges is shown in figure 3. In the wavelength range of about 400 nm to 1400 nm the laser beam is transmitted to the retina onto which it is focussed to a very small spot of the order of 10\(^{-20}\) \(\mu\)m. Consequently the irradiance on the retina is much larger than the irradiance on the cornea (up to a factor 100000) and therefore a comparatively small laser power is sufficient in this wavelength range (the "retinal hazard region") to damage the retina. It should be noted that the retinal hazard region comprises both the visible wavelengths (about 400 nm to 700 nm) and the near infrared region (700 nm to 1400 nm) where radiation is not visible but it is still focussed onto the retina (see figure 3).
• The wavelength range of 400 nm to 700 nm is defined as "visible" in the field of laser safety. However, it should be noted that there is no sharp dividing line between visible and non-visible: the sensitivity of the eye in respect of the visual stimulus is highest in the green, i.e. around 550 nm, and falls off towards red on one side and blue on the other. Radiation of 810 nm can also be seen when the intensity is correspondingly high. Cynical colleagues argue that with sufficient intensity, also 1064 nm Nd:YAG laser radiation can be seen, "but not for very long".
• **Figure 3:** The part of the electromagnetic radiation spectrum which is of interest in laser safety. Ultraviolet, mid- and far-infrared radiation is absorbed by the cornea and lens of the eye, while radiation in the wavelength range of 400 nm to 1400 nm is focused onto the retina, which results in very high irradiance levels on the retina even for small laser powers. Exposure of the skin with sufficiently high exposure levels results in skin injury.

• The ultraviolet and infrared region is further subdivided into wavelength regions which are relevant in terms of photobiological interactions:
Wavelength Considerations

An overview of effects in the different wavelength ranges is shown in figure below.
<table>
<thead>
<tr>
<th>CIE Shorthand</th>
<th>Wavelength Range</th>
<th>Tissue Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV-C</td>
<td>100 nm - 280 nm</td>
<td>absorbed in uppermost cell layers of eye and skin; highly effective in producing photokeratoconjunctivitis; germicidal. Radiation with wavelengths smaller than about 180 nm - 200 nm are heavily absorbed by the oxygen of the air and is also termed &quot;vacuum ultraviolet&quot;. Vacuum UV usually need not be considered for hazard evaluation.</td>
</tr>
<tr>
<td>UV-B</td>
<td>280 nm - 315 nm</td>
<td>intermediate absorption depth; highly effective in producing photokeratoconjunctivitis and sunburn</td>
</tr>
<tr>
<td>UV-A*</td>
<td>315 nm - 400 nm</td>
<td>penetrates deep into eye and skin; possible damage to the lens</td>
</tr>
<tr>
<td>IR-A*</td>
<td>700 nm - 1400 nm</td>
<td>radiation focussed onto the retina, but not visible; deep penetration into the skin</td>
</tr>
<tr>
<td>IR-B</td>
<td>1400 nm - 3000 nm</td>
<td>radiation absorbed in volume of the eye</td>
</tr>
<tr>
<td>IR-C</td>
<td>3000 nm - 1 mm</td>
<td>radiation absorbed in uppermost cell layers of eye and skin</td>
</tr>
</tbody>
</table>
The shorthand notation for wavelength ranges in the UV and IR are closely related to the absorption depth of radiation in tissue, which is described by the absorption coefficient. A natural exponential absorption law, the Beer Lambert law, applies and therefore the inverse of the absorption coefficient is a representative value for the depth at which the irradiance has fallen to $1/e$ of the value at the surface. Hence a large absorption coefficient corresponds to a small penetration depth. The absorption coefficient for water and tissue as function of wavelength is shown in figure 4.
**Figure 4:** Absorption coefficient as function of wavelength for water and tissue. It can be seen that the tissue absorption is governed by the water content of the tissue for infrared wavelengths and the absorption characteristics of hemoglobin and other organic molecules in the visible and in the UV. Blood for instance has a strong absorption in the blue and green part of the spectrum, and penetration depths into the skin are greatest for the red and near IR wavelengths.
Figure 5. The type of interaction of laser radiation with tissue will be determined by the interaction duration on the one hand and the irradiance on the other. For instance, photochemical interaction mechanisms are dominant for low irradiance, long term exposure, while non-linear effects only occur for short pulse, high irradiance exposure.
A larger spot will deliver a higher effective fluence at a given tissue depth.
This schematic representation (cross-sectional view) illustrates how the FEMTEC femtosecond laser system cuts a flap. The cornea (blue) is gently fixed with a curved patient interface (gray), and the laser focus is moved on a curved path at the desired depth of the cornea to cut the flap bed. Then, the laser focus is moved toward the anterior surface of the cornea in segmented ring cuts of decreasing depth to complete the flap. A section of the ring cuts is left unprocessed to create a defined hinge (A). After completion of the laser cut, the patient interface is removed, and the flap can be opened (B).
A surgical procedure of a flap cut with the FEMTEC femtosecond laser is shown. After completion of the laser cut, tiny microbubbles mark the treated area. Note the untreated segment of the side cut that defines the hinge (A). An SEM picture shows the sharp edges of the rim of a flap in a porcine eye under high magnification (B).