The Electromagnetic Wave and Medical Applications

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Abstract

The electromagnetic wave is strongly important and applicable to human life. It can be divided into 7 frequency ranges or 7 wavelength ranges which are radio wave, microwave, infrared, visible light, ultraviolet, X-rays and gamma rays. Each frequency has specifically different characteristics. These characteristics can apply widely such as communications, industrials, entertainment including medical professions. Especially in medical professions, the electromagnetic wave can be used directly and indirectly. The important examples of medical applications are microwave diathermy, X-ray medical imaging, radiosurgery, etc. Therefore, the study of electromagnetic wave characteristics in each frequencies will lead to highly medical advancement.

Keywords : Electromagnetic wave, Medical application, Frequency, Wavelength

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คลื่นแม่เหล็กไฟฟ้าและการประยุกต์ใช้ทางการแพทย์

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บทคัดย่อ

คลื่นแม่เหล็กไฟฟ้ามีความสำคัญ และสามารถนำมาประยุกต์ให้ประโยชน์กับชีวิตมนุษย์ได้เป็นอย่างมาก คลื่นแม่เหล็กไฟฟ้านี้แบ่งออกเป็น 7 ช่วงความถี่ หรือ 7 ช่วงความยาวคลื่น คือ คลื่นวิทยุ ไมโครเวฟ อินฟราเรด แสงที่ตาเห็น อัลตราไวโอเลต รังสีเอ็กซ์ รังสีแกมมา โดยแต่ละช่วงความถี่นี้จะมีคุณลักษณะที่แตกต่างกันออกไป คุณลักษณะเหล่านี้สามารถนำมาประยุกต์ใช้ให้เกิดประโยชน์ได้อย่างกว้างขวางทั้งในด้านการสื่อสาร ด้านอุตสาหกรรม บันเทิง รวมไปถึงด้านการแพทย์ โดยเฉพาะด้านการแพทย์นี้ มีการนำคลื่นแม่เหล็กไฟฟ้ามาประยุกต์ใช้ทั้งในทางตรง และทางอ้อม ตัวอย่างที่สำคัญของการนำคลื่นแม่เหล็กไฟฟ้ามาประยุกต์ใช้ทางการแพทย์ คือ การให้ความร้อนลึกด้วยคลื่นไมโครเวฟ (Microwave diathermy) การสร้างภาพทางการแพทย์ด้วยรังสีเอ็กซ์ (X-ray medical imaging) รังสีศัลยกรรม (Radiosurgery) ฯลฯ ทั้งนี้การศึกษาเรียนรู้คุณลักษณะของคลื่นแม่เหล็กไฟฟ้าแต่ละช่วงความถี่จะส่งผลให้เกิดความก้าวหน้าทางการแพทย์เป็นอย่างมาก

คำสำคัญ : คลื่นแม่เหล็กไฟฟ้า, การประยุกต์ทางการแพทย์, ความถี่, ความยาวคลื่น

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Introduction to Electromagnetic Wave

The electromagnetic wave is arisen by "electromagnetic disturbance" acted by change of electric field or magnetic field. In explanation, the electric filed is induced when magnetic field changes. On the other hand, the magnetic field is also induced when electric field changes.

The electromagnetic wave has all of standard wave properties which are reflection, refraction, Interference and diffraction, but there are some specific properties that differ from wave properties. In wave classification, it can be divided into 2 types according to their properties which are mechanical wave and electromagnetic wave. The mechanical wave such as sound wave, water wave and rope wave needs medium for propagation. The speed of mechanical wave depends on source and medium. The electromagnetic wave such as radio wave, microwave, light and X-ray does not need medium for propagation. It can transmit in space without medium. Moreover, the electromagnetic wave has the same speed in all frequencies. The speed of electromagnetic wave is $3x10^8$ m/s equaling to light speed (Peter et al., 2008).

In quantum theory, the electromagnetic wave consists of elementary particle or fundamental particle that is the smallest unit in general physics such as electron, positron and photon. This elementary particle can cause "electromagnetic interaction" that are source of electromagnetic wave (Perelomov and Terent'ev, 1967).

Structure of Electromagnetic wave

The electromagnetic wave is transverse wave that the vibration direction perpendiculars to propagation direction shown in figure 1. Since the electromagnetic wave arises from electromagnetic disturbance, it therefore consists of electric field and magnetic field. Each field is perpendicular together shown in figure 1. (Bakshi and Godse, 2009)

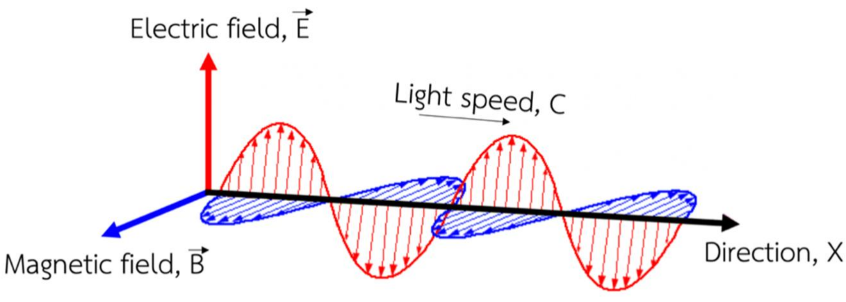


Figure 1. Structure of electromagnetic wave

According to figure 1., there are 3 axes, magnetic field, electric field and direction. Magnetic field, $\vec{B}$ and Electric field, $\vec{E}$ are perpendicular to the propagation direction, X. The perpendicular direction, that is the conventional $\vec{B}$ and $\vec{E}$, represents the amplitude of the magnetic field and electric field respectively. The direction axis (X), which is parallel to the propagation, represents the measure of propagation. It can be the distance, time or even the phase (Maxwell, 1865).

Spectrum of Electromagnetic Wave

Electromagnetic spectrum is the distribution of electromagnetic wave according to wavelength or frequency. Although all electromagnetic waves travel at the light speed, they have wide range of frequencies and photon energies. The electromagnetic spectrum consists of the span of all electromagnetic radiation referred commonly by frequency or wavelength ranges, such as radio wave or microwave radiation. Each ranges has different names based on different characteristics such as behavior, emission, transmission and absorption of the corresponding waves (Haitel, 2014).

In most of the electromagnetic wave ranges, a technique called spectroscopy is physically used to separate different frequencies or wavelengths of wave. This technique can produce a spectrum in order to show the constituency of frequencies or wavelength. Spectroscopy is also used to study the interactions of electromagnetic waves. The spectrums of electromagnetic wave sorted by frequency or wavelength are shown in figure 2 (Reza, 2020).

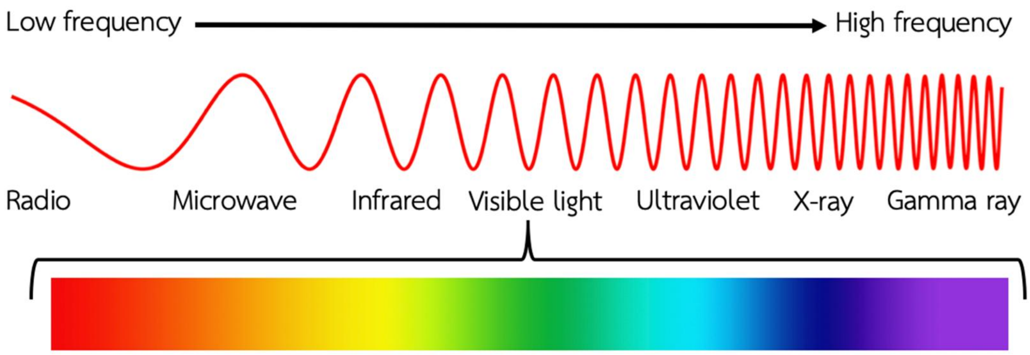


Figure 2. Spectrum of electromagnetic wave

According to figure 2, the spectrums of electromagnetic wave can be divided into 7 bands which are radio, microwave, infrared, visible light, ultraviolet, x-ray and gamma ray. Radio wave has the lowest frequency (longest wavelength, 625-740 nm), and gamma ray has the highest frequency (shortest wavelength, 380-435 nm). Human eye cannot recognize the spectrum of electromagnetic wave excepting visible light. Each band has some unique characteristics that can be used for many applications such as communications, industrials, entertainments including medical professions (Mehta, 2011).

Electromagnetic Wave in Medical Application

One of the most useful electromagnetic wave applications is medical professions that all of frequency bands can apply to medical applications. This section explains how electromagnetic wave applies to medical applications. The explanation arranges from low frequency to high frequency.

1. Radio wave

Radio wave is the lowest frequency (the longest wavelength) of electromagnetic wave emitted and received by antennas, that have conductors such as metal rod resonators. In order to generate radio wave, a transmitter generates an alternating current (AC) applying to an antenna. The oscillated electrons in the antenna generate electric and magnetic fields radiating from the antenna as radio wave. According to radio wave receiver, the electric and magnetic fields of radio wave couple to the electrons in an antenna that create alternating current (AC) applied to a radio receiver. The radio wave mainly transparences in the earth's atmosphere, but it can be reflected at the ionosphere shown in figure 3.

According to figure 3, the radio wave can be divided into 3 parts depending on its transmission. The radio wave reflected by ionosphere is called "sky wave". The radio wave sent between antennas directly is called "space wave". Finally, the radio wave sent by antenna to receiver directly is called "surface wave".

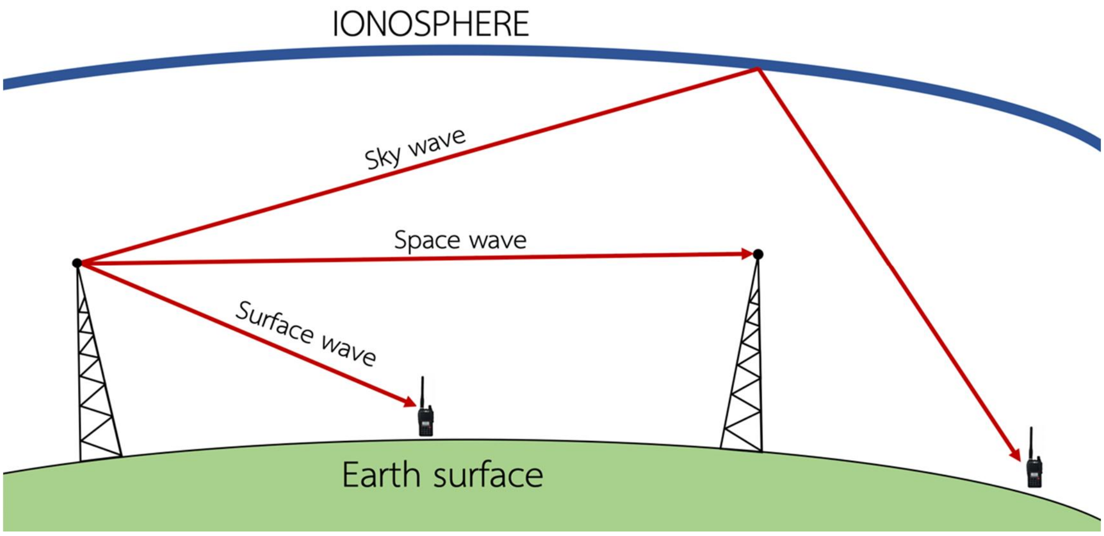
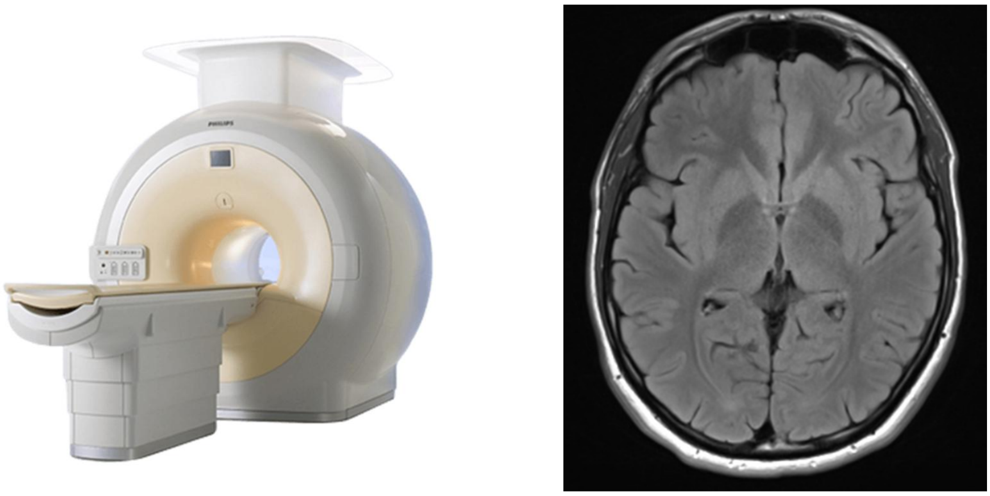


Figure 3. Radio wave transmission

The radio wave can apply to medical applications indirectly. It can send signal to call for help or communicate between patient and medical personnel in wilderness area such as deep forest and mountain that telephone signal cannot reach (Liu et al, 2019).

Moreover, Radio wave can also apply to medical imaging application called MRI (Magnetic Resonance Imaging). MRI is medical imaging technique used in radiology. It can diagnose anatomy and physiology of human body using physical reaction of magnetic field, radio wave and proton in human tissue. Proton particles in human tissue move from equilibrium position to plane of magnetic field when they receive energy of radio wave. After energy transfer between photon particles and radio wave ends, photon particles move back to equilibrium position and emit the energy. Finally, the energy emitted from proton particles can be use to create medical imaging of human tissue.



a.) b.)

Figure 4. a.) MRI machine (Indiamart, 2008)
b.) Example of MRI image (Di Muzio, 2015)

2. Microwave

Microwave has higher frequency than radio waves. Wavelength of microwave is shorter than radio wave, from 1 millimeter to 10 centimeters. Microwave energy is produced by magnetron and klystron tubes. Microwave is not only emitted and absorbed by short antennas, but it is also absorbed by polar molecules. Unlike ordinary higher frequency waves such as ultraviolet, light and infrared, they are absorbed mainly at material surfaces. Microwave can penetrate into material and collect their energy inside the material surface. According to this characteristic, microwave can apply to heat food. In addition, metal pipe called “waveguide” is used to carry the microwave energy. At the low end of the microwave band (300 MHz), the microwave can propagate through the atmosphere, but at the high end of the microwave band (300 GHz), microwave is absorbed by atmospheric gasses limiting the propagation distances to a few kilometers (Harrison et al., 2020).

Microwave does not use only food heating application, but it can also apply to many applications. Wavelength of microwave is used in radar, satellite communication and wireless networking technologies (Wi-Fi).

In medical application, microwave can apply deep heat to human body called “microwave diathermy”. In practical, microwave diathermy has 2 important properties using in clinical advantage. First, microwave is absorbed by tissues having high water content such as muscle. This technique suites to treat pathologic processes in human muscles and fat. Second, microwave is more easily to focus than the short waves used in short wave diathermy. Moreover, microwave can reduce energy leaking and generate heat more efficient than short wave (Goats, 1990).

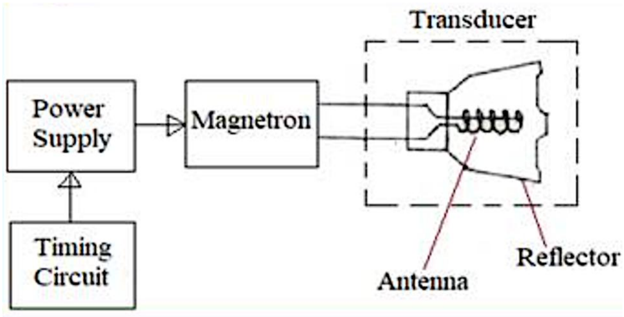


Figure 5. Microwave diathermy (RF Wireless World, 2012)

3. Infrared

The electromagnetic wave ranged between 300 GHz to 400 THz (1 mm – 750 nm of wavelength) approximately is called Infrared. The infrared can be divided into 3 parts.

The first part of infrared called “Far-infrared” (300 GHz to 30 THz) is the lower part of range sometimes called “terahertz waves”. Far-infrared is absorbed by phonons in solids, molecular motions in liquids, and rotational mode in gas molecules.

The second part of infrared is called “Mid-infrared” (30 to 120 THz). The black-body radiator can radiate strongly in this range. Moreover, human skin radiates mid-infrared strongly at the low end of this part. This part is sometimes called “the fingerprint region”.

The final part of infrared is called “Near-infrared” (120 to 400 THz). The physical processes relating to this part are the same as visible light. Moreover, the highest frequency of this part is detected by photographic film directly and by many types of solid state image sensors in order to use for infrared videography and photography.

In medical application, infrared radiation can use to relief of muscle pain and tension. The infrared radiation strikes biological tissue causing molecules to vibrate. Because of this effect, the temperature of biological tissue will rise. Since human tissue has amount of water, the water absorption for infrared can be determined by penetration depth.

The high level of infrared region (short wavelength, 780–1,400 nanometers) called “IR-A”. This IR-A radiation can penetrate up to some 5 millimeters into human skin allowing to reach the hypodermis directly. Normally, the shorter the wavelength causes the greater the penetration depth. Therefore, the “IR-C” with 3,000 nanometers – 1 millimeter of wavelength and “IR-B” with 1,400–3,000 nanometers are absorbed in the upper layer of human skin called “the epidermis”. Moreover, the thermal effects of IR-A cover a larger volume than IR-B and IR-C.

Infrared radiation can stimulate local blood circulation that can relieve muscle pain and tension, and it also can treat autoimmune diseases or wound-healing disorders too. However, according to heat production of infrared, it may be harmful to do so. Therefore, it must always be assessed by a doctor.

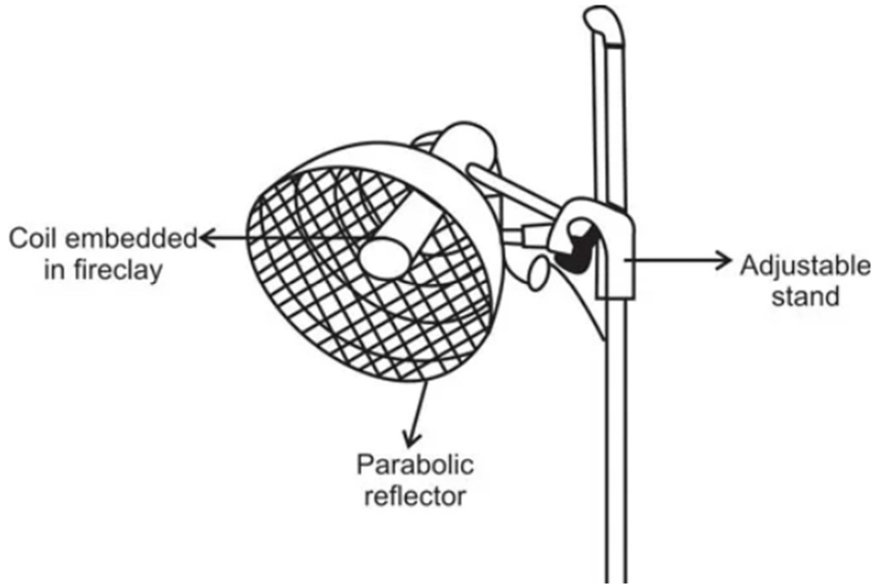
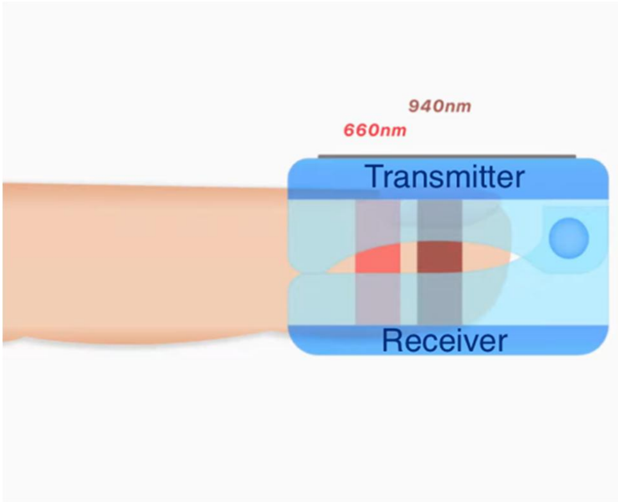


Figure 6. Infrared lamp (Vaishali Ladva, 2021)

Moreover, Infrared can apply to Finger Pulse Oximeter in order to measure Oxygen saturation called “SpO_2” which is a measurement of oxygen that your blood is carrying as a percentage of the maximum that it could carry. Normally, the SpO_2 should be between 96% to 99%. It is not only Finger Pulse Oximeter, but also some smart watches that use infrared to measure SpO_2. These devices can identify Oxyhemoglobin (hemoglobin with oxygen) and Deoxyhemoglobin (hemoglobin without oxygen) in red blood cell. They use “light absorption principle”. Finger Pulse Oximeter sends two wavelength of infrared (660 nm and 940 nm) passing thru human skin to receiver shown in figure 7. The Oxyhemoglobin and Deoxyhemoglobin absorb infrared in different values. Therefore, received light can be calculated into Oxyhemoglobin and Deoxyhemoglobin. Finally, Oxyhemoglobin and Deoxyhemoglobin can be calculated into SpO_2 by following equation.

$$SpO_2 = \text{Oxyhemoglobin} / (\text{Oxyhemoglobin} - \text{Deoxyhemoglobin}) \times 100 \quad (1)$$

In Covid-19 situation, Finger Pulse Oximeter is very important tool to indicate symptom level of infected patient.



a.) b.)

Figure 7. a.) Finger Pulse Oximeter (Aly, 2021)
b.) The operation of Finger Pulse Oximeter (Phol, 2021).

4. Visible light

Visible light is emitted powerfully by the sun, although, all wavelengths radiated by the sun show that the sun emits infrared more than visible light slightly. Human eye can recognize the electromagnetic spectrum in this range. Visible light is normally absorbed and emitted by electrons atoms moving from one energy level to another. According to this action, it allows the chemical mechanisms causing human vision and plant photosynthesis. Visible light having frequencies between 400–790 terahertz (380 nm - 760 nm of wavelength) is detected by the human eye perceived as visible light.

According to visible light, white light is a combination of different frequencies in the visible spectrum. A prism splits white light up into the several colors when white light passes through it. This phenomenon is shown in figure 8.

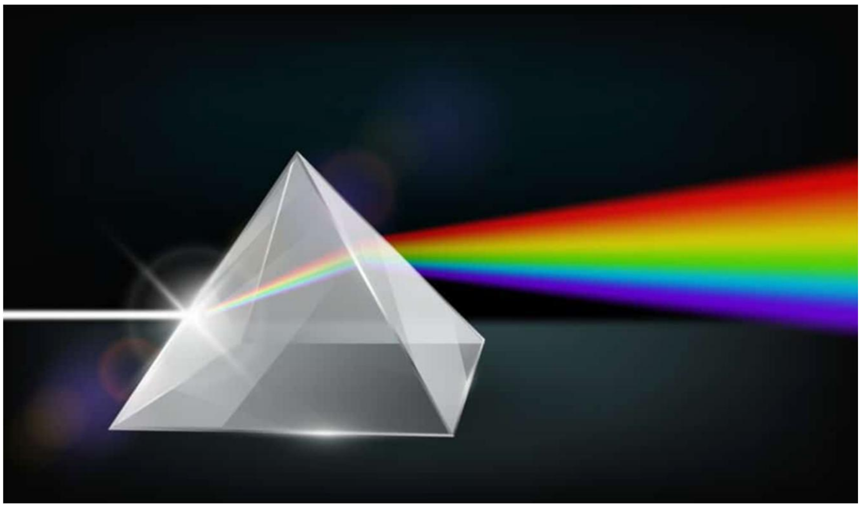


Figure 8. White light split by prism (Science spark, 2019)

If the Electromagnetic spectrum having a frequency in visible region reflects an object then strikes the eyes, this results cause a visual perception of the scene. Then, the brain visual system processes the plenty of reflected frequencies into different colors and shades.

In application of visible light, optical fiber transmitting the visible light can carry information. Therefore, optical fiber mostly uses for signal cable such as computer networking, massive automotive industry, television cable and providing internet services.

For medical application, optical fiber can be use in surgery and dentistry called "Endoscopy" which is used for visualize using optical fiber. According to the assistance of this cable, the visible light can transmit inside the body. Moreover, this technique can reduce the incision size created by the surgery.

Moreover, some wavelengths of visible light can apply to laser (light amplification by stimulated emission of radiation) that is really useful in many applications. Laser is monochromatic and coherent light with high energy. The examples of lasers having wavelength of visible light are Helium-Neon (He-Ne, 632.8 nm) with red light can stimulate wrinkled skin in order to regenerate new cell, Argon ion (Ar^+, 488 nm and 514.5 nm) with green light can pass cornea without damage and treat the broken retina, Ruby (694.3 nm) with red light and dye laser (585 nm) with green light can apply to delete red birthmark.

On the other hand, there are some lasers that are not identified in visible light, but they also use in medical applications. For example, Diode laser (800 - 1,350 nm) and Holmium YAG (Ho-YAG) can treat spinal disc herniation. They also use in hair elimination. Erbium YAG (Er-YAG, 2,940 nm) can treat atrophic scars. Neodymium-doped YAG (Nd-YAG, 1,064 nm) can eliminate leg hair. Alexandrite laser (755 nm) is suitable for hair removal with white skin people. Carbon dioxide laser (CO_2 laser, 10,600 nm) can eliminate wart, polyp, freckles, mole and fleck.

Figure 9. Laser Hair Removal Machine (Sandra, 2014)

5. Ultraviolet

The electromagnetic wave having higher frequencies next to visible light is called ultraviolet or UV. Therefore, the wavelength of ultraviolet is shorter than the visible spectrum. Ultraviolet radiation is the longest wavelength that the photon energy suffices to separate electrons from atoms called "ionization". Thus, it causes chemical reactions shown in figure 8. Short wavelength of ultraviolet can damage living tissue. In addition, the ultraviolet can react to many substances to glow with visible light called fluorescence applied to fluorescent lamp.

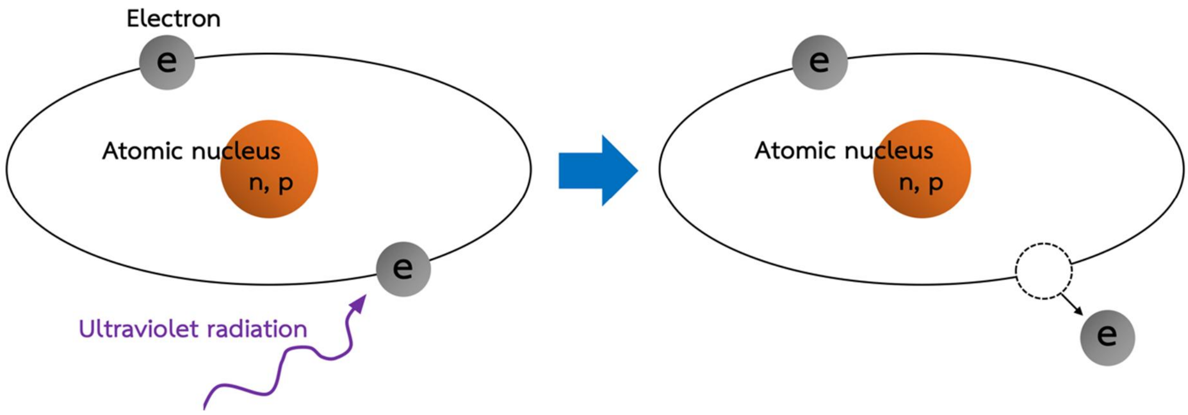


Figure 10. Ionization reaction

At the middle range of ultraviolet, it cannot react the ionization, but it can break chemical bonds that make molecules reactive. According to sunburn, it is the destructive effects on skin cells caused by middle range ultraviolet radiation, which causes the skin cancer mainly. In the middle range of ultraviolet, it can damage the complex DNA molecules causing a potent mutagen.

The Sun emits ultraviolet about approximately 10% of its total power including extremely short wavelength of ultraviolet that can destroy most life on the earth. However, most of damaging wavelengths are absorbed by the atmosphere. Moreover, most of the ultraviolet in the middle range is also blocked by the ozone absorbing strongly in the 200–315 nm of wavelength. Therefore, less than 3% of ultraviolet emitted by the sun transmits to sea level. The remainders from sun light are UV-A and some UV-B. The UV-C is blocked ozone layer. The lowest energy range of ultraviolet between 315 nm of wavelength and visible light called UV-A is not blocked by the atmosphere shown in figure 11, but it does less biological damage.

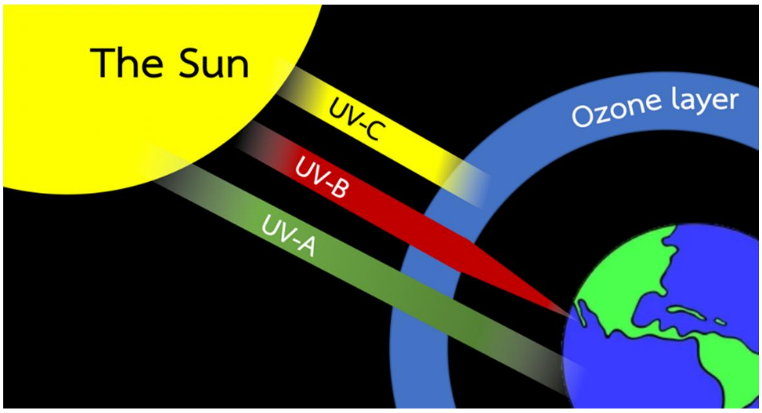


Figure 11. The ultraviolet emitted by the sun

In medical application, since the ultraviolet can damage to DNA molecules, it is used to sterilize medical tools. Therefore, UV can use widely in COVID-19 situation in order to sterilize medical tools, examination room, operating room, emergency room, etc. shown in figure 12.

Moreover, the ultraviolet with high energy can activate human skin to produce more vitamin D treating some skin diseases. Finally, the ultraviolet also can treat rickets in human.

Figure 12. Ultraviolet emitted by robot sterilizes a hospital room (AP, 2013)

6. X-rays

The higher frequency range next to ultraviolet is called “X-rays”. The X-ray has 10^{16} – 10^{19} Hz of frequency or 10^{-12} – 10^{-9} m of its wavelength. Because of high frequency, X-ray can pass thru the material. It also has ionization reaction property like the upper ranges of ultraviolet. However, due to their higher energies, X-rays can also interact with matter called “Compton effect”. X-rays can be divided into 2 types which are hard X-rays and soft X-rays. Hard X-rays has shorter wavelengths than soft X-rays. Hard X-rays can pass through many types of substances with little absorption. Therefore, they can be used in order to see through the thicknesses objects.

In order to produce X-rays, it can be produced by CRT (Cathode Ray Tube). According to CRT, electrons are accelerated to impact the metal target. After that, the energy is emitted in term of heat and X-rays.

X-rays can apply to medical applications. One of favorite use is called "diagnostic X-ray imaging" sometimes called "radiography". The principle of X-ray imaging is that X-rays can pass human tissues, but it cannot pass human bones. Therefore, X-rays passing human tissues impacts to film causing black color on film, and X-rays reflected by human bones causes white color on film shown in figure 14 (Herman, 2009).

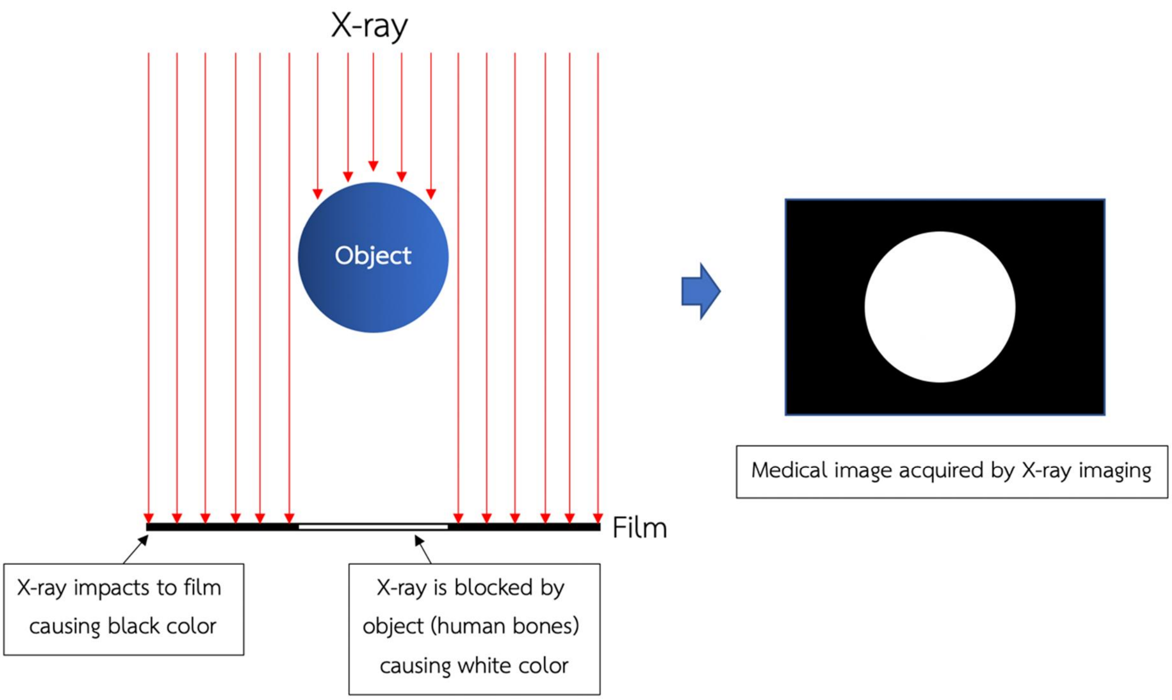


Figure 13. Diagnostic X-ray imaging process

Figure 14. Example of X-rays imaging (Herman, 2009)

Moreover, X-rays can apply with computer image processing in order to check organ abnormalities called “Computed Tomography Scan” or “CT Scan”. The X-rays is projected transversely to targeted organ. Then, computer generates and receives medical image of targeted organ. This received image is 3D image, and it can be divided into many cross section images shown in figure 15. This technique has more details and accuracies than ordinary X-ray image that cannot show depth of targeted organ.

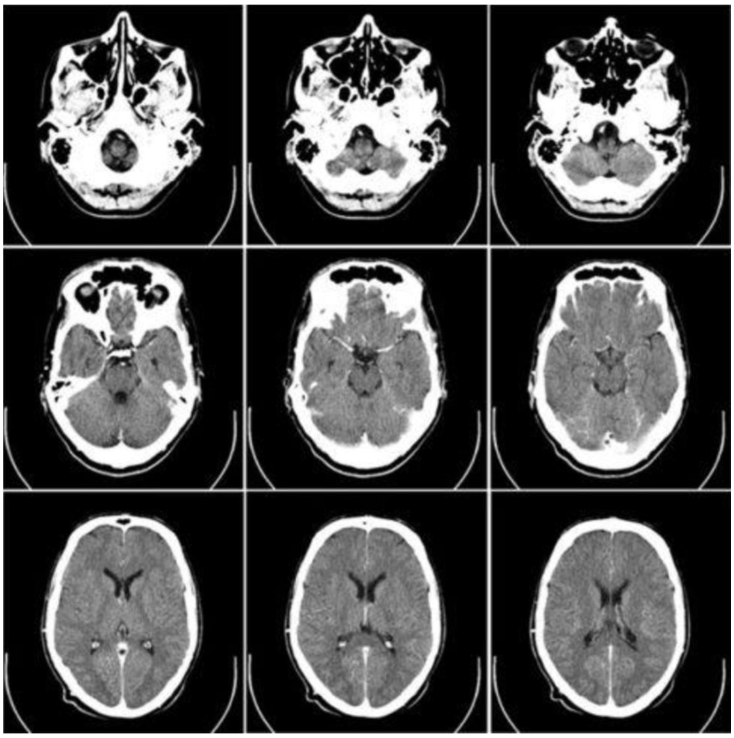


Figure 15. CT Scan image of Human head (Neurologie Zeeland, 2022).

Figure 16. CT Scan machine (Avanti, 2022).

7. Gamma rays

Gamma rays has the highest frequency which is 10^{20} – 10^{22} Hz approximately. It has the shortest wavelength of electromagnetic wave (10 pm – 100 fm). It also has the most energetic photons. It has no defined lower limit to their wavelength for now. In astronomy, it is very important to study high-energy regions. Gamma rays can be used by physicists in order to study its penetrating ability (Galloway, 2015).

Gamma rays also can be used for irradiation of foods and seeds for sterilization. According to medical application, gamma rays is used for diagnostic imaging in nuclear medicine such as positron emission tomography (PET) scan. PET scan can generate image of biochemical activity of human body. It can show cell damage rate and high sugar metabolism of cancerous cells. In order to operating PET scan, the small amount of radioactive substance called “fluorodeoxyglucose” or “FDG” is injected into the bloodstream and accumulates in the body where it gives off energy in the form of gamma rays. The FDG is detected by the PET scanner. Then, computer converts the signals into detailed images showing how tissue and organs are working.

Another technique called Ga-68 Dotatate PET/CT scan. The Ga-68 dotatate is a radiopharmaceutical used during PET scans operation. Some PET/CT combination scanners also run a CT scan in the same session. Then, the received images of each technique are merged together. The Ga-68 PET/CT full-body scan can capture neuroendocrine tumors (NETs) that overexpress somatostatin receptors and show where the tumors are in the body (Christophe et. al., 2016).

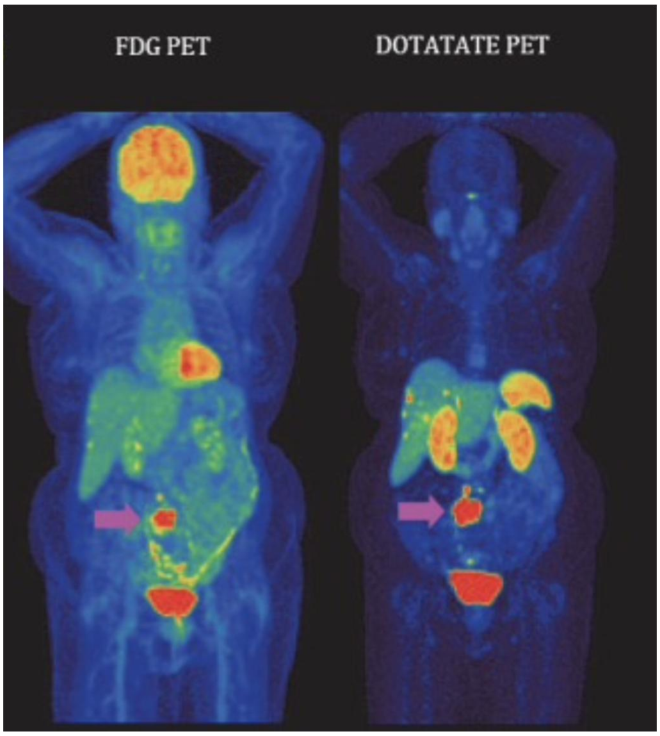


Figure 17. Example of the full body scan of FDG PET and Ga-68 PET/CT (Aslani et al, 2014)

Moreover, gamma rays can also use to treat cancerous tissues called "Radiosurgery". The radiosurgery sometimes called stereotactic radiosurgery, is a precise form of therapeutic radiology. The radiosurgery does not involve actual surgery (Leksell, 1983). The very focused beams of gamma rays radiation are used to treat cancerous tissues without a surgical incision or opening.

Figure 18. The radiosurgery (Elekta, 2022).

Now, medical tools have many functions. They also have different operations. Therefore, medical tools need to be classified and tested in order to define their standards of each tool. The specific standards of medical tools are called "Particular standards". Each medical tool has specific code. Thus, the efficiency test of each medical tool is different. For example, the ultrasonic machine needs IEC 60601-1-5 standard, and X-rays needs IEC 60601-2-7.

The specific standards of medical tool have more than 50 standards and are enforced Internationally. Therefore, user need to consider these specific standards in order to guarantee the quality and safety of medical tools especially the medical tools that radiate electromagnetic wave (Webstore, 2022).

Conclusion

The electromagnetic wave with 7 ranges divided by frequencies or wavelengths has very importance to human life. It is not only medical applications, but also routine applications. Each range of electromagnetic wave has specific characteristics. Therefore, it can apply widely. According to medical application, Electromagnetic wave has direct and indirect applications depending on characteristics of its frequency or wavelength range. In direct application, electromagnetic wave can treat muscle from pain and tension in microwave range, disinfect bacteria and germs in ultraviolet range, create medical image in X-rays range, and treat cancer in gamma rays. For indirect application, electromagnetic wave can transmit and receive signal in area without telephone signal using radio range.

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