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Review Article

Electromagnetic radiation in modern medicine: Physical and biophysical properties

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ARTICLE INFO

Article history:
Received 7 June 2012
Accepted 16 July 2012

Keywords:
Electromagnetic
Radiation
Physical Biophysical
Properties
Modern
Medicine

ABSTRACT

Introduction: The widespread application of electromagnetic radiation (EMR) in modern medicine requires healthcare professionals and undergraduates to be familiar with its physical and biological properties.
Aim: The aim of this paper was to review current literature on EMR physical principles.
Materials and methods: Available literature on EMR has been reviewed and grouped thematically.
Results and discussion: The electromagnetic spectrum is divided into radio waves, microwaves, infrared, visible, ultraviolet, X-, gamma- and cosmic rays. Electromagnetic waves (EMWs) are characterized by frequency, velocity, period of vibration and wavelength. Depending on the medium, EMR may decelerate, reflect, refract, diffract, interfere or polarize. These phenomena apply to EMWs (light waves), pressure and water waves. The wave-particle duality of radiation is widely accepted and explains its nature and mechanism of action. Principles of quantum mechanics help to predict the potential biological impact of EMR.
Conclusions: From humble beginnings, more than 100 years ago, EMR has become an important component of modern medicine. Therefore, there exists an urgent need for education and better understanding with respect to its principles and applications.

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1230-8013/$ - see front matter
http://dx.doi.org/10.1016/j.poamed.2012.07.002

1. Introduction

The electromagnetic spectrum is traditionally divided into radio (Hertz) waves, microwaves (MWs) (radar), infrared, visible, ultraviolet, X-, gamma- and cosmic rays (Fig. 1). The boundaries between these electromagnetic regions and subregions are not hard and fast ones. The bounds of visible light are determined by the physiology of the human eye. The visible subregions range from about 0.40 μm (blue end) to 0.78 μm (red end) and serve as a good example of the non-uniqueness of the subbands of regions. Table 1 shows the approximate wavelengths and frequencies of key electromagnetic bands. Hence, as the boundaries of particular ranges of electromagnetic radiation (EMR) are conventional and not sharp, radiation of the same length can be known as radio wave or microwave, depending on the application.[3,6,10,11,13,17]

2. Materials and methods

Available literature on EMR has been reviewed and grouped thematically.

3. Aim

The widespread application of EMR in modern medicine requires healthcare professionals and undergraduates to possess some knowledge of its physical and biological properties. This paper discusses the biophysical principles of EMR, its interactions with living organisms and its application in clinical practice.

4. Results and discussion

4.1. *Physical properties of EMR*

EMR is produced by the coupled activity of alternating electric and magnetic fields, which propagates itself in space as a transverse EMW or as a stream of small portions (quanta) of energy called photons. The wave nature of EMR dominates in long waves, MW, infrared, ultraviolet, visible light, and laser radiation. Cosmic-, gamma- and X-rays are more commonly perceived as a stream of photons.

Similar to mechanical waves, electromagnetic waves are characterized by frequency (f), velocity (v) of propagation in the medium, period of vibration (T) and wavelength (λ). The movement of an electromagnetic beam in vacuum occurs with a constant, maximum speed for any form of energy ($c = 299\,792\,458$ m/s). The speed of EMWs changes as they cross between different media, but their frequency remains constant. Fission (dispersion) depends on the density of the medium and a wavelength and frequency. It accounts for the deceleration of the wave in a gas, liquid or solid medium. Its speed is always lower than in vacuum. EMW velocity is directly proportional to its frequency and wavelength. Frequency and wavelength of a particular type of EMWs are always related. High frequency corresponds with short waves and low frequency with long

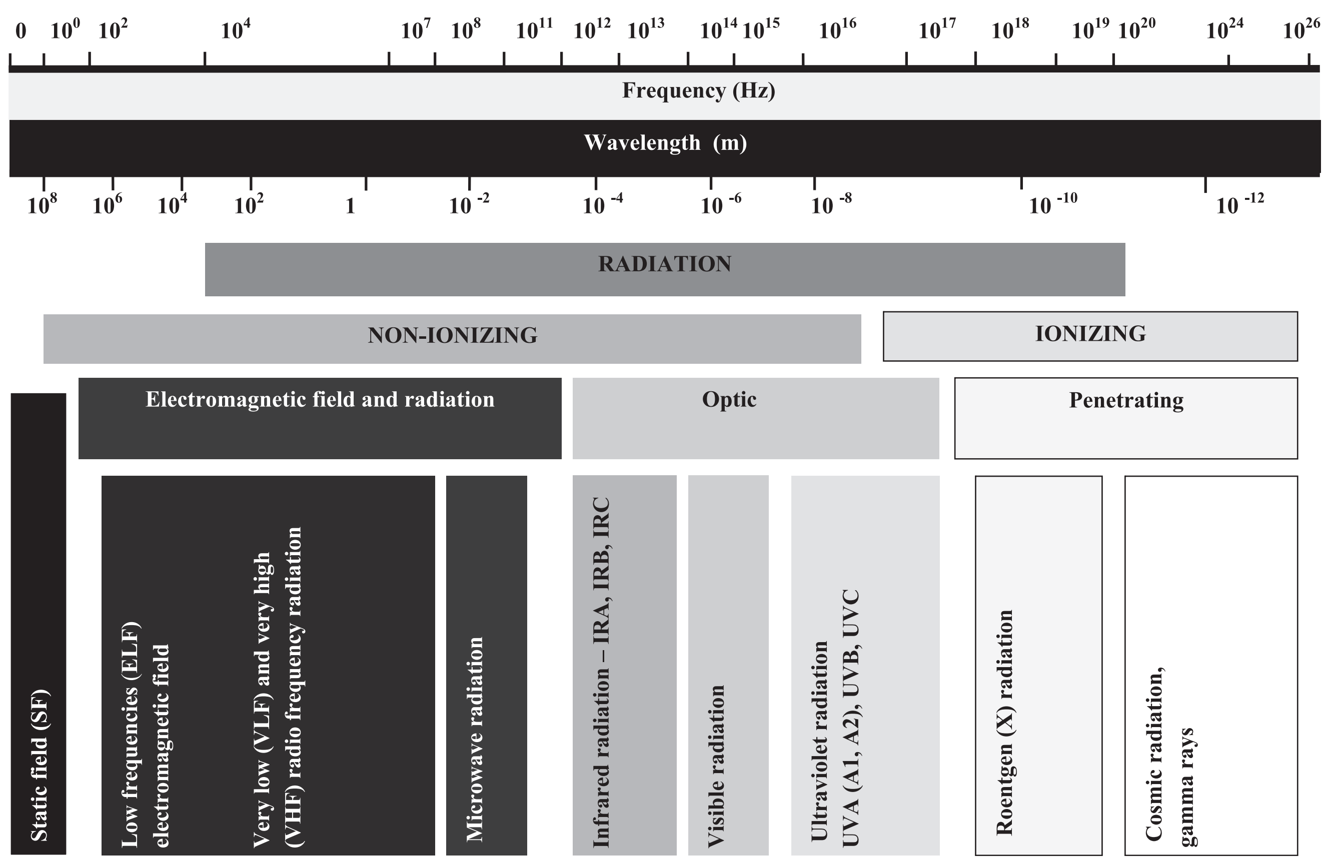

Fig. 1 – Electromagnetic spectrum.[13]

Table 1 – Approximate wavelengths and frequencies of key electromagnetic bands.[7]

Key radio bands		
Designation	**Wavelengths (m)**	**Frequencies (MHz)**
AM radio waves	560–190	0.540–1.600
TV waves	5.50–0.33	54–890
FM radio waves	3.40–2.78	88.1–108.1
Cell phone waves	0.43, 0.35, 0.18, 0.16, 0.14	700, 850, 1700, 1900, 2100
Satellite radio waves	0.129–0.128	2320–2345
WiFi waves	0.124–0.121	2412–2480
Radar waves	300–0.001	1–300 000
Primary infrared (IR) bands		
Color	**Wavelengths (μm)**	**Frequencies ($\times 10^{14}$ Hz)**
Far IR	1000–10	3×10^{-3}–0.3
IR-C	10.0–3.0	0.3–1.0
IR-B	3.0–1.4	1.00–2.14
IR-A	1.4–0.7	2.14–4.28
Primary visible color bands		
Color	**Wavelengths (nm)**	**Frequencies ($\times 10^{14}$ Hz)**
Red	780–625	3.8–4.8
Orange	625–590	4.8–5.1
Yellow	590–565	5.1–5.3
Green	565–500	5.3–6.0
Blue	500–435	6.0–6.9
Violet	435–380	6.9–7.9
Primary ultraviolet (UV) bands		
Designation	**Wavelengths (nm)**	**Frequencies ($\times 10^{14}$ Hz)**
UVA	400–320	7.45–9.37
UVB	320–280	9.37–10.7
UVC	280–200	10.7–15.0
Vacuum UV	200–50	15.0–60.0
Extreme UV	80–2.5	37.5–1.2×10^3
Soft X-ray	4.5–0.15	$(0.7–2.0) \times 10^4$

wavelengths. The frequency of light determines its color; higher frequency corresponding to blue and lower frequency to red end of the spectrum.[6,11,14,13,19]

Depending on the nature of the medium, EMR may decelerate, reflect, refract, diffract, interfere or polarize. All these phenomena apply to EMWs, pressure and water waves. Reflection of EMWs, similar to the reflection of light, can be regular or diffuse. The angle of reflection is equal to the angle of incidence in regular reflection. However, when the reflecting surface is uneven (diffuse reflection) these are different. Collapse of a wave, similar to light refraction, changes its direction of propagation and occurs when it crosses the boundary between two, usually homogenous, media. Diffraction (wave deflection) is the simultaneous change of direction and shape of the surface of an expanding wave when it encounters a non-homogeneous medium. Diffraction of light leads to a characteristic blurring of the boundaries between light and shadow. Interference or overlap (superposition) of two or more waves of the same frequency results in the strengthening or weakening of the generated wave. EMWs able to interfere are consistent (coherent), e.g., lasers; if they do not interfere, they are inconsistent (electric light bulb).[3,11,14,13,17,19]

Reflection or refraction of EMR by anisotropic crystals leads to polarization and rearrangement of the direction of vibration of the electric and magnetic field vectors. In a linearly polarized beam electromagnetic field oscillations occur in one direction; in non-polarized radiation in different directions. Visible incoherent polarized (VIP) light, Solaris, Bioptron, Bionic, or polychromatic incoherent low energy radiation (PILEMR) devices produce polarized radiation.[4,12,14,13,18]

4.2. *The quantum theory of EMR*

Quantum (corpuscular) nature of EMR explains the nature of cosmic, gamma or X-ray radiation. In 1900 Max Planck proposed the quantum theory based on a theoretical “black body” which absorbs the entire radiation incident upon it. Planck postulated that the emission and absorption of radiation by atoms and molecules of any substance can occur only in portions (quanta), with a minimum value of the emitted or absorbed photon energy.[2,6,13,17]

Hallwachs provided the direct proof of the quantum nature of EMR by describing the photoelectric effect, in which incident radiation liberates electrons from solids (metals). Einstein confirmed that the nature of this phenomenon depends on the individual act of the collision of a photon with an electron in metals. Compton measured the length of scattered X-rays. He proved that the wavelength of scattered radiation is greater than the wavelength of incident radiation; it increases with the scattering angle and does not depend on the scattering facility. Compton also postulated that photon has energy and defined momentum.[3,6,13,17,18,19]

Nowadays, the wave-particle duality of radiation explains the nature and mechanism of X-rays and gamma radiation. Quantum mechanics allows one to predict their potential biological impact and employ them in diagnostics and treatment.[3,6,15,17]

4.3. *Biophysical properties of ionizing radiation*

The nature of EMR and its potential to ionize determines its impact on humans. Ionizing radiation (IR) liberates electrons from the last orbit of an atom, thus transforming it into a positive ion. Living organisms absorb IR through the photoelectric effect, Compton scattering and creation of pairs of oppositely charged electrons. The intensity of the photoelectric effect depends on the energy of radiation and the atomic number of the tissue. The lower the number and the higher the energy, the more frequently the photoelectric effect occurs. In contrast to the photoelectric effect, an electron in the Compton scattering phenomenon does not absorb all the energy of a photon and subsequent ionization is caused by both photon and electron. The frequency of this phenomenon is inversely proportional to the radiation energy and independent of the atomic number of the tissue. The pairing effect occurs when a photon interacts in the nucleus of an atom in such a way that a pair of oppositely charged electrons arises. Positively charged electron (positron) ionizes the environment and is annihilated after a collision with a negatively charged electron. This results in two photons of opposite direction. Incidence of this phenomenon is proportional to the logarithm of the photon energy and the atomic mass of the tissue.[1,9,16,17]

4.4. *Biophysical properties of non-ionizing radiation*

Non-ionizing radiation (NIR) includes all components of the electromagnetic spectrum with a frequency lower than the frequency of vibration of the gamma rays and ultraviolet portion adjacent to gamma radiation. The depth of the penetration of NIR in the human body depends on wavelength and frequency, angle of incidence, intensity of radiation, structure and vasculature of irradiated tissue, and skin pigmentation. Inhomogeneity of a human body complicates the issue.[5,7,13,15] Hair, clothing, skin thickness and texture, thickness and water content of deep tissues markedly influence the absorption of EMR. Penetration and absorption of EMR within tissues are reduced by an uneven body surface.[5,8,13]

5. Conclusions

From humble beginnings, more than 100 years ago, EMR has become the lynchpin of modern medicine, diagnostics and physiotherapy. Educating healthcare professionals and an improved understanding of EMR principles and applications are, therefore, needed.

Conflict of interest

None declared.

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