2 From Sun to Therapeutic wIRA

W. Müller, H. Piazena, and Peter Vaupel

2.1 Introduction

Everybody realizes intuitively that "sunshine" can be beneficial and invigorating. This also applies to animals and plants. There are first indications that the radiation of the sun was used for therapy and wellness since 1400 B.C. [1]. "Heliotherapy" is one of the oldest treatments humans have intentionally applied for disease prevention and health improvement. The role of the sun for all life on Earth has been recognized at a very early stage. In almost all cultures, people have developed sun cults, which are supposed to be an intuitive appreciation of the importance of the sun. There are profound reasons for this. As part of the solar system, Earth arose after the sun and was always exposed to the solar radiation. As a consequence, whatever happened on Earth took place under the influence of the sun.

Assuming that primeval forms of life arose in water, water was at the same time the element for chemical reactions, and a means of transport for dissolved substances, and environment. Energy available in the radiation of the sun probably acted as a stimulating factor. Fossils in stromatolites of the primeval seas of the archaean verify that cyanobacteria have performed photosynthesis with the aid of

W. Müller (✉)
Physical Optics Consultant Office, Wetzlar, Germany
e-mail: h.-werner.mueller@t-online.de

H. Piazena
Department of Anaesthesiology and Intensive Care Medicine, Charité - Universitätsmedizin Berlin, Corporative Member of Freie Universität Berlin and Humboldt Universität zu Berlin, Berlin, Germany

P. Vaupel
Department of Radiation Oncology, University Medical Center, University of Freiburg, Freiburg/Breisgau, Germany

German Cancer Consortium (DKTK) Partner Site Freiburg, German Cancer Research Center (DKFZ), Heidelberg, Germany

P. Vaupel (ed.), *Water-filtered Infrared A (wIRA) Irradiation*,
https://doi.org/10.1007/978-3-030-92880-3_2

the solar radiation billions of years ago [2]. In order to get a better understanding about the nature of this radiation, it is mandatory to have a closer look at how it is produced.

2.2 Generation of the Electromagnetic Radiation in the Sun

The huge amount of energy emitted by the sun is generated by nuclear fusion. The temperature in the core of the sun is about 15×10^6 K, as indicated in Fig. 2.1a. The kinetic energy of atomic particles in this core is correspondingly high. Under these conditions and with the aid of the tunnel effect, by which a particle can pass through a potential energy barrier that is *higher* than its own energy and can overcome mutual repulsions, hydrogen is fused into helium in a multistep process as shown in Fig. 2.1b.

The cycle starts with the collision of two protons to form a deuteron (deuterium nucleus) with the simultaneous creation of a positron and a neutrino. When the positron encounters a free electron, both particles annihilate. Their mass energy is converted into two γ-photons (γ-rays) with high energy, according to Einstein's law:

$$E = \Delta m \cdot c^2 \tag{2.1}$$

where Δm = mass loss in the nuclear fusion, and c = phase velocity of light.

When the deuteron collides with a proton, a helium nucleus is created together with a γ-photon.

The overall equation is as follows:

$$4\,{}^1\mathrm{H} + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu + 6\gamma \tag{2.2}$$

and the energy emitted into the space amounts to $\Delta E = 26.2\ MeV$ [4].

2.2.1 The Extra-Terrestrial Solar Spectrum

On its way to the photosphere (see Fig. 2.1a), observable from Earth as the surface of the sun, every γ-photon has its own individual fate. In nearly all cases, it loses energy because of interactions with other atomic particles before it is emitted into the space. Absorptions and re-emissions take place. Photons are also scattered within short distances, and a continuous spectrum of photons, related to their energies, is created. This spectrum of electromagnetic waves can be expressed according to Max Planck's law which connects the energy of a photon with the frequency and the wavelength of an electromagnetic wave, respectively (wave-particle-duality):

$$E = h \cdot \nu = h \cdot \frac{c}{\lambda} \tag{2.3}$$

where E = energy, c = velocity of the light, λ = wavelength, h = Planck's constant, and ν = frequency.

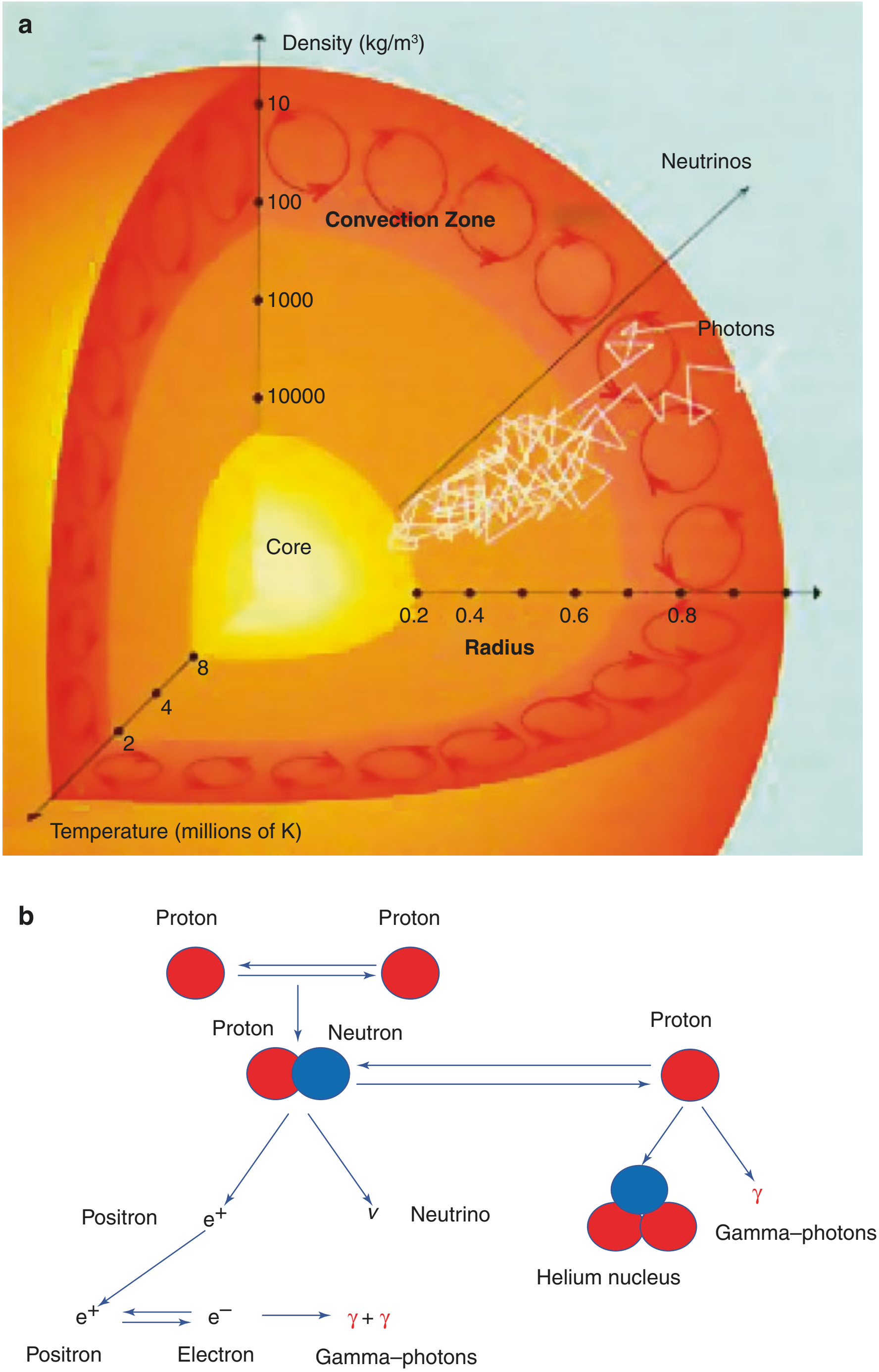

Fig. 2.1 (**a**) Internal structure of the sun. The radius numbers show the distance from the center related to the total sun radius of about 700,000 km. The way of the γ-photons (γ-rays) from the core to the surface and the decrease of their number is indicated by white zigzag lines (permission granted by Dr. Margarita Metaxa) [3]. (**b**) Multistep process of the nuclear fusion, in which hydrogen is burned into helium

In this spectrum, the proportion of the γ-photons is small as expected. Photons with less energy cover a wide range, which extends from 10^{-11} m to 10^{8} m (see Fig. 2.2). For historical reasons, this spectrum has been arbitrarily subdivided into regions (ranges) based on different wavelengths [5].

This extra-terrestrial solar spectrum has a characteristic shape (see Fig. 2.3, curve 2) and has a maximum at 500 nm (blue-green light). The spectrum is superimposed by emission and absorption lines (Fraunhofer lines) that are mainly caused by gases in the photosphere of the sun at temperatures of about 5800 K. It can be approximated by a black body spectrum at 6000 K and can, therefore, be described mathematically with Planck's radiation law.

Planck's radiation law describes the spectral radiant exitance of electromagnetic radiation emitted by a black body in thermal equilibrium at a given temperature T. In the following form, it mathematically describes the differential spectral radiant exitance of an area A [7]:

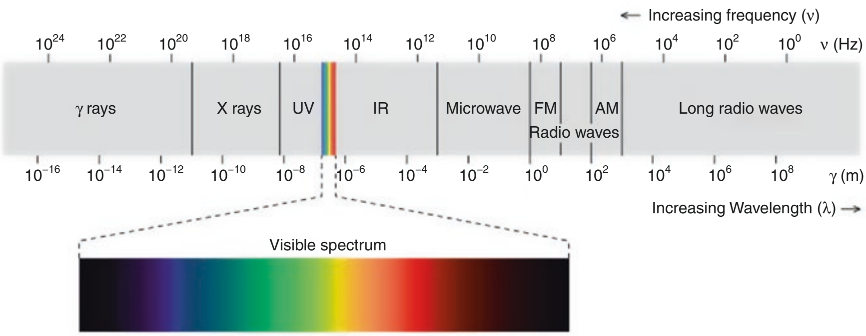

Fig. 2.2 The spectrum of electromagnetic waves emitted from the sun, subdivided into spectral regions. Author: Philip Ronan. Permission granted under the terms of the GNU Free Documentation Licence [5]

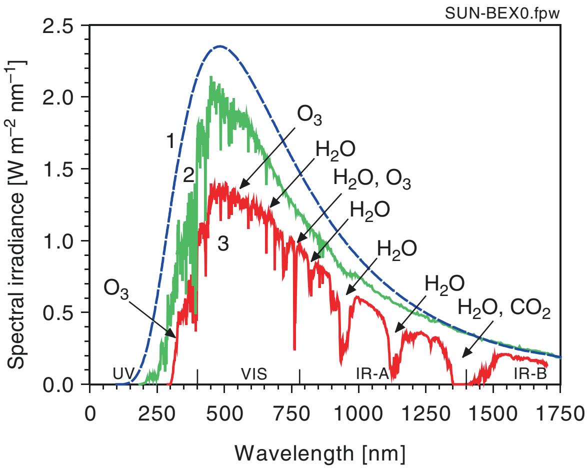

Fig. 2.3 Spectral irradiance as a function of wavelength. Curve 1 (blue): Black body spectral irradiance at 6000 K (data normalized for comparison). Curve 2 (green): Extra-terrestrial solar spectral irradiance [6]. Curve 3 (red): terrestrial solar spectral irradiance measured in Berlin on 2. July 2008 at noontime and clear sky (solar elevation angle = 50°)

$$dM_\lambda = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{e^{\left(\frac{hc}{k\lambda T}\right)-1}} d\lambda \tag{2.4}$$

where dM_λ = differential radiant exitance in the wavelength interval $d\lambda$, c = $2.9979 \cdot 10^8$ ms^{-1} (vacuum velocity of the light), $h = 6.6256 \cdot 10^{-34}$ Ws^2 (Planck constant), and $k = 1.38054 \cdot 10^{-23}$ JK^{-1} (Boltzmann constant).

Other formulas can be derived from this theoretical superstructure. By differentiation, Wien's displacement law is obtained (first described by Wilhelm Wien, independent of Max Planck):

$$\lambda_{\text{max}} = \frac{b}{T} \tag{2.5}$$

where λ_{max}= wavelength of the maximal spectral exitance of a black body, and b = 2897.8 µmK (Wien's displacement constant).

Equation (2.5) shows the inverse relationship between the wavelength of the emission maxima and the temperature. At higher temperatures, the maxima are shifted to smaller wavelengths (see Fig. 2.4).

By integration, the Stefan–Boltzmann law can be derived, describing the power radiated from a black body as a function of its temperature (earlier deduced by Josef Stefan and Ludwig Boltzmann):

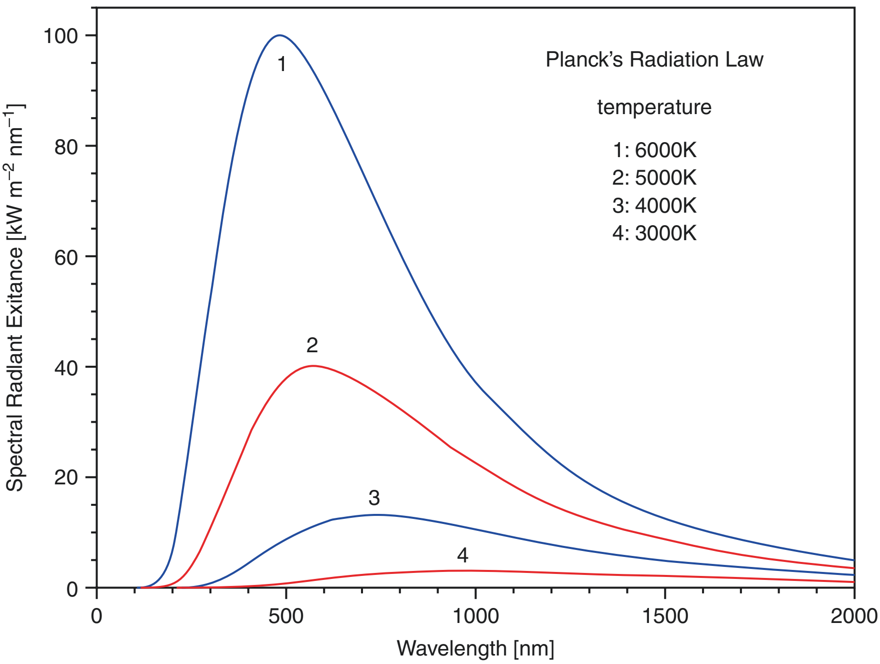

Fig. 2.4 Characteristic radiation curves of a black body at different temperatures covered by Planck's radiation law

$$M = \sigma \cdot T^4 \tag{2.6}$$

where M = radiant exitance, $\sigma = 5.67032 \cdot 10^{-8}$ Wm^{-2} K^{-4} (Stefan–Boltzmann constant), and T = absolute temperature [K].

2.2.2 The Terrestrial Solar Spectrum

Before radiation from the sun reaches Earth, it must pass the terrestrial atmosphere.

The solar spectrum on Earth exhibits strong absorption lines and bands indicating interactions of the radiation with gases in the atmosphere (see Fig. 2.3, curve 3).

As soon as water was on Earth, it was also in the atmosphere, mainly as water vapor. The first forms of life in water that were developed during evolution were exposed to solar radiation which was filtered through the water which was contained in the atmosphere and in their environment.

When the first living creatures colonized the land from sea, filtering by their original habitat was lost and they became continuously exposed to the solar radiation which was water-filtered in the atmosphere. Besides atmospheric ozone which absorbs short-wavelength UV radiation, and carbon dioxide which is responsible for thermal buffering in the atmosphere, the water in the atmosphere protects life from overheating by IR-B and IR-C and thereby provides suitable thermal conditions on Earth. Water-filtered IR-A has therefore influenced life during evolution until today.

2.3 The Generation of Absorption Lines and Bands (Water Bands) in the Terrestrial Spectrum, Interaction Between Water Molecules, and Electromagnetic Radiation (Photons)

2.3.1 Structure of the Water Molecule and Hydrogen Bonding

Decisive for the interaction between water molecules and photons is the structure of the water molecule. It consists of two hydrogen molecules and one oxygen molecule forming a triangle (see Fig. 2.5a).

Since the negative electrical charge of an oxygen atom is greater than the positive charge of a hydrogen atom, the electrons of the covalent bonds are drawn to the oxygen molecule. The center of both positive charges is spatially separated from the center of the negative charge, thereby creating a dipole. This dipole can take up energy from an electromagnetic field, and since covalent bonds have a certain amount of elasticity, the energy is converted into kinetic energy, e.g., in the form of *vibrations* along the binding arms and in *rotations* (see below).

Another property of the dipole character allows water molecules to interact with each other. The more positive part (H) approaches the more negative part (O) of a molecule in the neighborhood to create a hydrogen bond [9]. In this way, molecular spatial clusters are formed, and the individual molecules are restricted in their movement (see Fig. 2.5b, c).

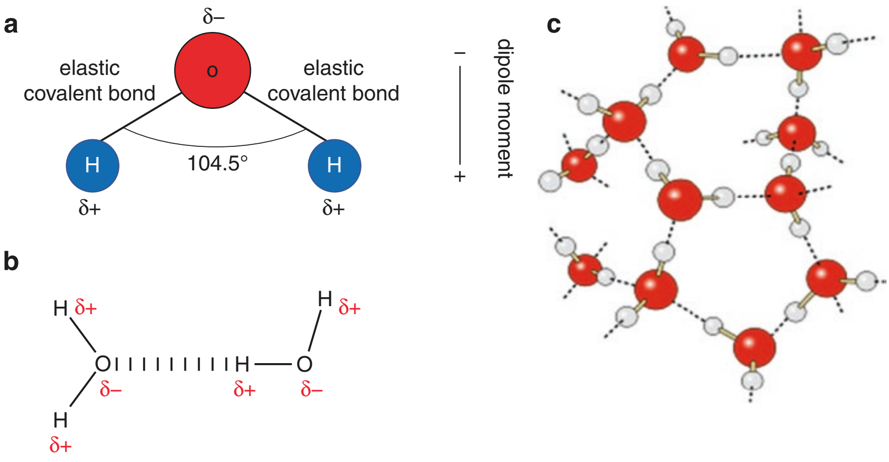

Fig. 2.5 Structure of the water molecule: (**a**) ball and stick model, with the angle between the atoms causing the dipole character of the molecule, (**b**) hydrogen bonds (Author: Benjah-bmm27, public domain [8]), and (**c**) water clusters, discrete hydrogen-bonded assemblies of water molecules. Author: Raimund Apfelbach, public domain [9]

2.3.2 Vibrations of the Water Molecule

2.3.2.1 Fundamental Vibrations

The freely movable water molecule (in water vapor) can vibrate in three basic ways: symmetrical stretching, asymmetrical stretching, and bending (see Fig. 2.6). Transitions from the lowest possible energy state of the molecules to the first excited state in these different vibrational modes are indicated by ν_1, ν_2, and ν_3. Energy required for excitations is supplied - in quanta - by photons, usually expressed in wavelengths [10].

The excited states are characterized by quantum numbers n. $n = 0$ describes the ground state, $n = 1$ the first excited state, etc. (see Fig. 2.6). The wavelengths related to the basic stretch vibrations are in the infrared-B (IR-B) range (1.4–3.0 μm), and the wavelength for bending is in the IR-C range (3–1000 μm). The energy for transitions from the ground state into higher excited states with, for example, two or three times the basic frequency, is taken from photons with smaller wavelengths and can cause absorption lines up into the red region of the visible spectrum (see Fig. 2.7) [10].

According to quantum physics, the higher the step of excitation, the lower the probability that it will occur and the lower the expression of the absorption line. This explains why in the terrestrial solar spectrum the most pronounced absorption bands are in the IR-A range.

2.3.2.2 Combination Vibrations

Vibrations can be composed of basic vibrations like $\nu_1 + \nu_2$ or $\nu_1 + \nu_2 + \nu_3$ or $2\,\nu_3 + 1\nu_1$. The corresponding energies are added, the absorption lines are shifted to smaller wavelengths. This kind of vibration, called *combination vibration*, provides

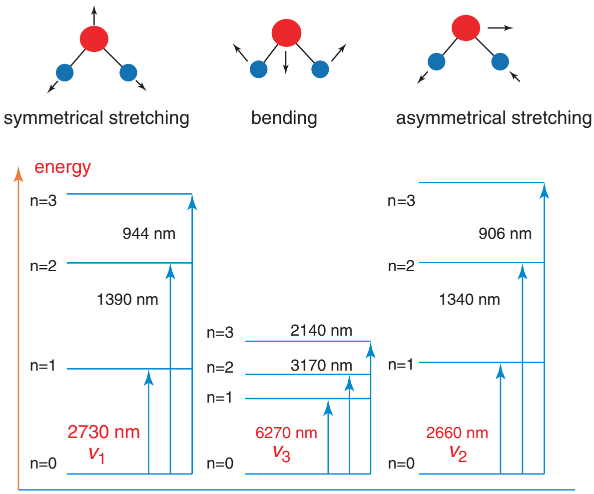

Fig. 2.6 Basic vibration modes of the water molecule and their characteristic energy levels in the ground state and in selected vibrationally excited states described by quantum numbers. The wavelengths of the radiation absorbed by such a molecule during its transition from the ground state to these excited states are also shown [10]

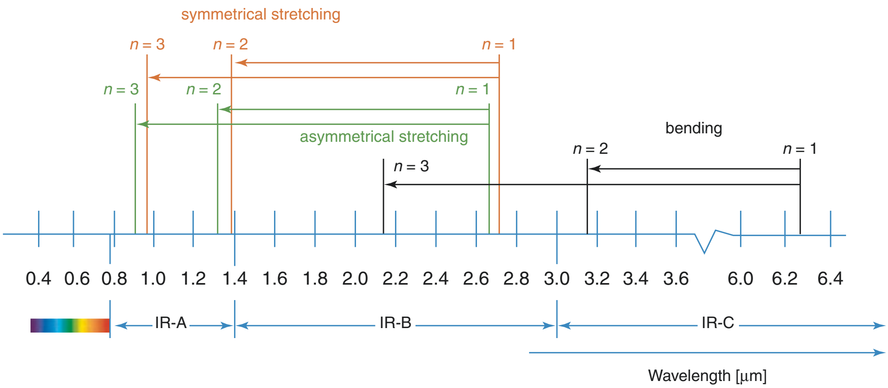

Fig. 2.7 Shift of the basic absorption lines after different steps of excitation

numerous combination possibilities. Combination bands are observed when more than two or more fundamental vibrations are excited simultaneously. Their energies can be close together to form pronounced absorption bands. They are marked by the quantum numbers related to the kinds of vibration $(\nu_1, \nu_2, \nu_3) \rightarrow (2,1,0)$ [11, 12].

2.3.2.3 Rotations

In addition to basic vibrations, rotations can increase the kinetic energy of the water molecule. There are three independent axes of rotation, which all go through the center of gravity close to the oxygen atom (see Fig. 2.8).

The rotation around each of these axes has its own moment of inertia (distribution of the mass related to the axis of rotation). Consequently, the rotational spectrum has no obvious structure. Since the moments of inertia on rotation are very small, the energies required for excitations are correspondingly small and the

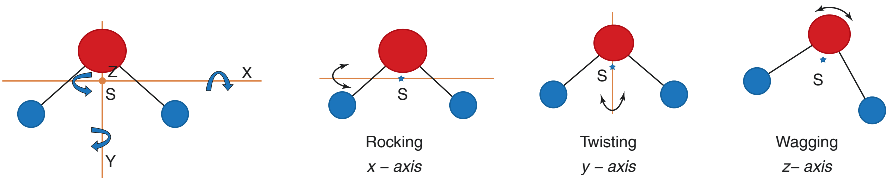

Fig. 2.8 Axes of rotation of the water molecule [13], and the different kinds of rotation related to these axes, with different moments of inertia

absorption lines are in the IR-B and IR-C range, in the microwave range, and in the range of radio waves. In liquid water, the movements of the molecules are considerably restricted by hydrogen bonds. Stretch vibrations require less energy, and rotations are reduced to librations [14, 15], i.e., the molecules no longer rotate, but only oscillate around their axis of rotation: They rotate back and forth. The absorption lines are shifted to longer wavelengths.

Basically, in liquid water each molecule is influenced by its surrounding matrix and creates its own absorption behavior related to the environment in which it is currently located. Summation of all single absorption lines results in a more or less broad absorption band.

The most important conclusions from these processes are as follows: (a) The energy absorbed by water molecules of solar radiation is exclusively converted into kinetic energy that means into heat; since the water content of soft tissues varies between 30–85% [16], *water is the key chromophore/absorber for hyperthermia*; (b) the water content in the tissue allows for detection of locally growing superficial tumors (surrounded by normal tissue) by temperature measurements (e.g., with an IR-camera), because most tumors contain 2–3 times more (interstitial) water than normal tissues [17] and, therefore, can "preferentially" be heated; (c) for thermal therapy (syn. thermotherapy), the water bands are decisive. Before radiation hits the skin, the number of photons within these bands must be reduced. If this would not occur, high irradiation in these bands would preferentially heat up upper tissue layers, which could result in non-tolerable heat-induced pain and thereby prevent effective heating of deeper tissue layers. Water-filtered radiation thus reduces the risk of overheating body surfaces and allows for deeper penetration of the rest of the spectrum into the tissue.

In fair skin and underlying tissues, the absorption coefficients of the main chromophores (absorbers) have relative minima in the region between about 600 nm and 1300 nm (visible light and IR-A) (see Fig. 2.9). In this region, called the *optical window*, two effects come together: reduction of the irradiation in the water bands, mainly in the IR-A region and absorption minima of other absorbers. Therefore, the IR-A region is most important for tissue heating.

2.4 Generating Therapeutic wIRA

The generation of therapeutic wIRA requires an electromagnetic spectrum, which aligns with the most important characteristics of the terrestrial solar spectrum:

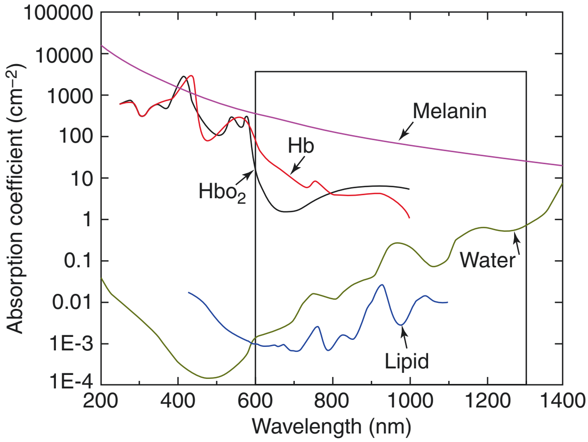

Fig. 2.9 Absorption coefficient spectra of various tissue chromophores ([18] Free PMC article). The spectra within the "optical window" (marked by the rectangle) show relative minima

1. The spectrum should be continuous, similar to the spectrum of a black body.
2. Its maximum should be in the IR-A region.
3. The radiation has to be water-filtered.
4. The radiation power should be higher than that of the sun.

Among all radiation sources, filament lamps best fulfill these criteria, especially halogen lamps. Therefore, in the wIRA-radiator, a 750 W halogen lamp is installed with a correlated color temperature CCT of about 2900 K (see Fig. 2.13a). According to Wien's displacement law, the maximum is at around 1082 nm, approximately in the middle of the IR-A region, as needed (see Fig. 2.10a).

A 7-mm-thick water layer in a hermetically sealed cuvette is used to "water filter" the spectrum. This thickness is an empirical compromise between the need to decrease irradiance within the water absorption bands and achieve the irradiance outside these bands, which is required for therapy.

2.5 Comparison Between Therapeutic wIRA and the Terrestrial Solar Spectrum

There is a great congruence between therapeutic wIRA and the terrestrial solar spectrum (see Fig. 2.11). The small shift of absorption bands to longer wavelengths because of hydrogen bonding is not relevant. The much higher spectral irradiance of wIRA in the IR-A than that of the solar spectrum enables adaptations to specific therapeutic needs as required.

As mentioned above, the water bands are more strongly expressed in the IR-A range due to the higher probability for lower step excitations of the water molecules requiring energy from the IR-A. The absorption lines in the visual part of the spectrum are only slightly pronounced. In principle, they can increase tissue heating, but their contribution, related to those of the bands in the IR-A, is small and can, therefore, be neglected.

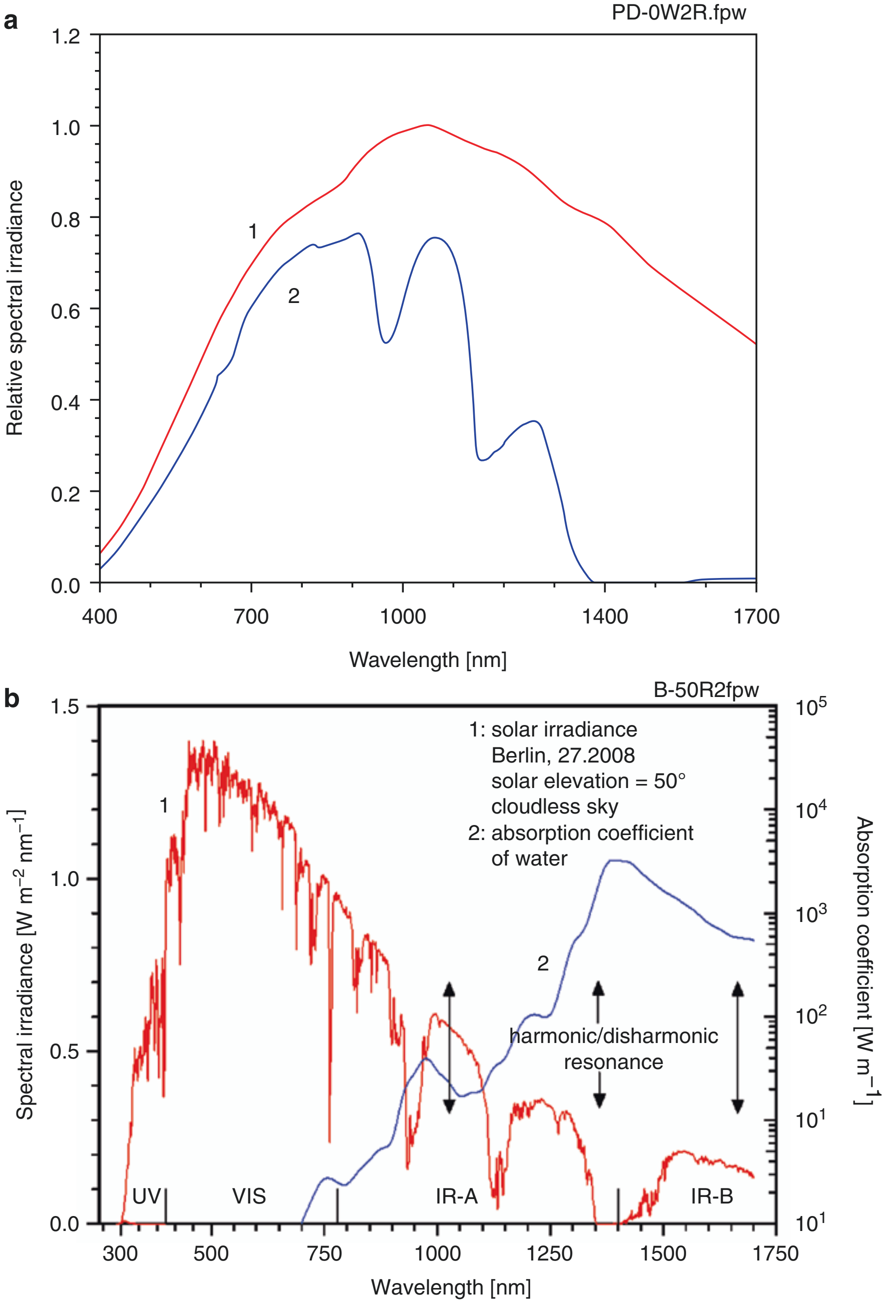

Fig. 2.10 (**a**) Curve 1: spectral irradiance of the 750 W halogen lamp (unfiltered), curve 2: spectral irradiance of the lamp after passing through a 7-mm water filter. (**b**) Comparison of spectra of solar terrestrial irradiance and absorption by water showing that the most significant areas of overlap occur in the region of 800–1300 nm, reducing the irradiance of solar radiation [19]

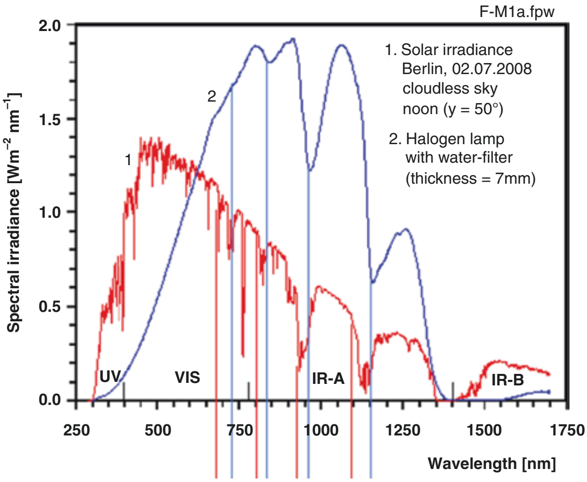

Fig. 2.11 Spectral irradiance of the water-filtered halogen lamp and of the terrestial midday sun in comparison. The shift of the absorption bands to longer wavelengths because of hydrogen bonding is obvious. Vertical red lines indicate the wavelengths of the absorption bands in the solar spectrum, and vertical blue lines indicate those of the halogen radiation filtered by liquid water [11]. It must be considered that additional substances in the atmosphere can influence shape and position of the absorption bands in the terrestrial spectrum

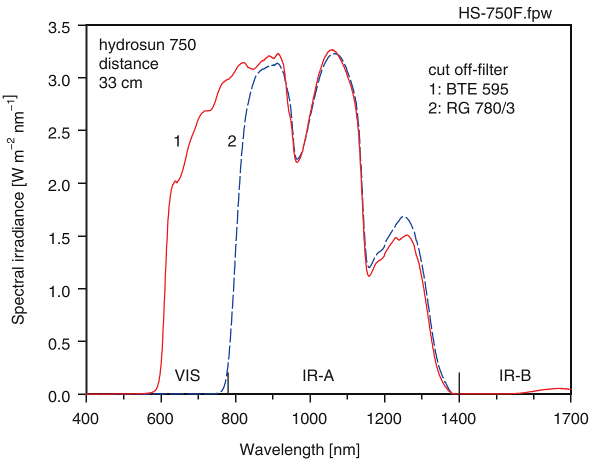

Fig. 2.12 Selection of wIRA spectra with the aid of optical filters. Curve 1: the wIRA spectrum with visible radiation for functional control of the wIRA radiator and marking the target field. Curve 2: the pure wIRA spectrum

A cut-off filter (type RG 780) is used for pure wIRA irradiation (see Fig. 2.12). If a part of the visible irradiation is desired (e.g., for easy visual control of radiator function and marking of treatment fields. *Note*: Pure IR-A is not visible!), a cut-off filter (type BTE 595) is recommended (see Fig. 2.12).

2.6 The wIRA Radiator

The wIRA radiator (type Hydrosun 750, Hydrosun, Müllheim/Baden, Germany) is schematically shown in Fig. 2.13a. In this wIRA radiator, the halogen lamp is placed in the focal point of a concave mirror collimating most of the radiation. The filter bracket acts as a diaphragm. Because the lamp filament is not a point radiation source and reflection of the concave mirror does not completely create a parallel beam, the main radiation is somewhat divergent (see Fig. 2.13b).

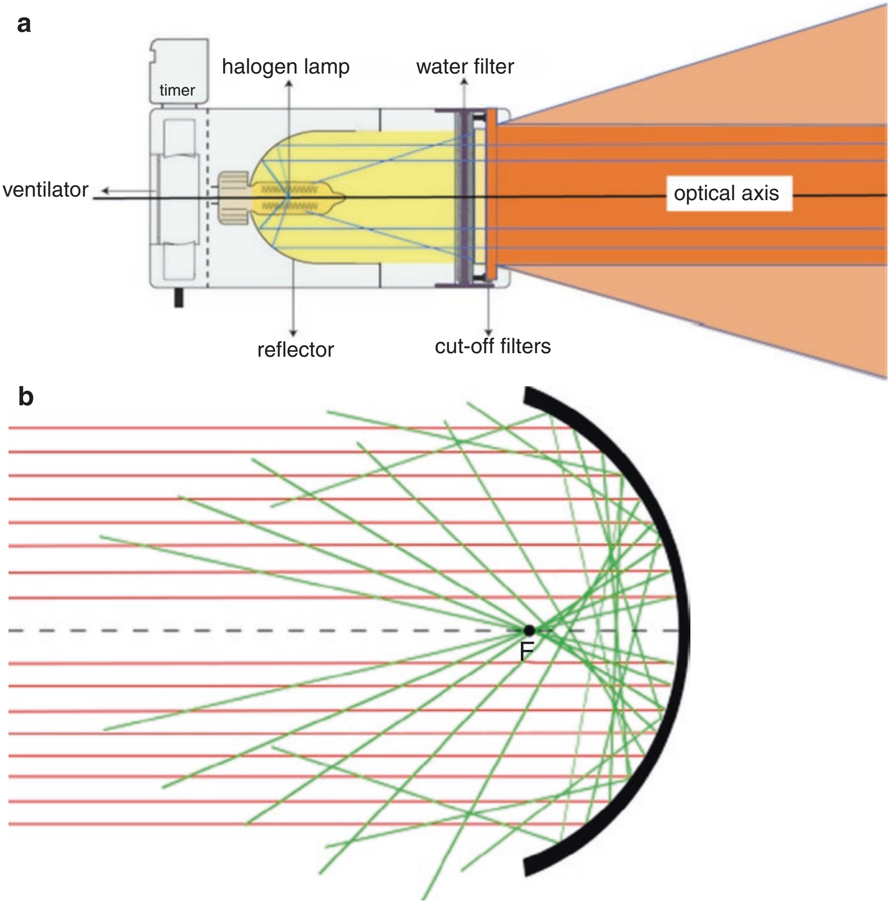

Fig. 2.13 (**a**) Scheme (cross-section) of the Hydrosun wIRA radiator (type *Hydrosun 750,* Hydrosun Medizintechnik, Müllheim/Baden, Germany). Courtesy of Hydrosun Medizintechnik, Müllheim/Baden, Germany), (**b**) collimation of radiation by a concave mirror inside the irradiator. Author: Synkizz. Permission by creative-commons-license 3.0 [20]

2.6.1 Characteristics of Therapeutically Applied wIRA Irradiation

2.6.1.1 Setting the Desired Irradiance

Depending on the therapeutic effect to be achieved, irradiance can be adapted by varying the distance between the wIRA radiator exit and the target area (patient). In this way, the spectrum is not altered. Varying the power supply of the lamp instead would influence the emitted spectrum according to Wien's displacement law (Fig. 2.14).

2.6.1.2 Homogeneity of wIRA

To avoid heterogeneous heating of the target area, the homogeneity of the irradiation has to be monitored. As shown in Fig. 2.15, the size of the homogeneously irradiated area depends on the distance between radiator exit and target. Even in the case of two combined radiators, the homogeneity in a considerably enlarged treatment field is sufficient, despite the overlap (Fig. 2.15b).

2.6.1.3 Combination of Two wIRA Radiators

In cases of large-sized lesions, combining two wIRA radiators enlarges the treatment field considerably (see Fig. 2.15b). The optimal distance between the two radiators can be assessed by real-time thermography. In addition, they can be adjusted in different angles according to individual requirements of the treatment field.

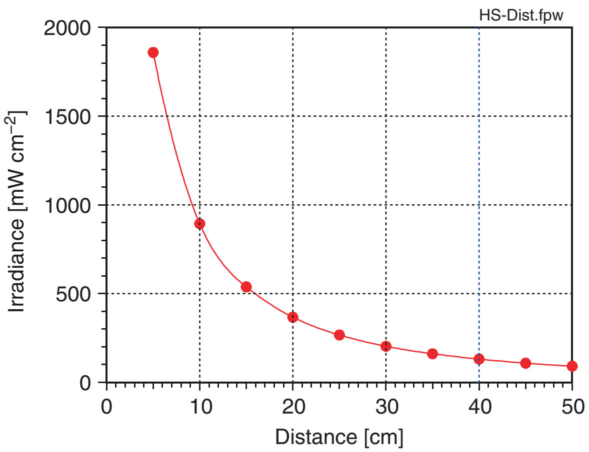

Fig. 2.14 Irradiance of wIRA as a function of the distance between the radiator exit and the target area

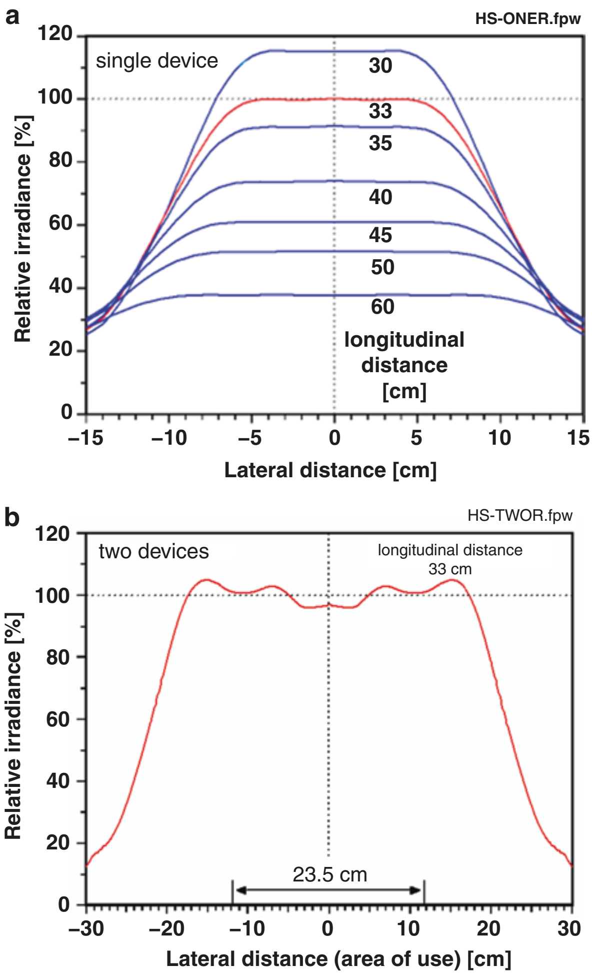

Fig. 2.15 Lateral distribution of the irradiance as a function of the distance between the wIRA radiator exit and the target area. (**a**) single radiator [21]. (**b**) Combination of two radiators. The lateral distance of their axes is 23.5 cm, with 33 cm between the radiator exit and the target area [21]

2.7 Conclusions

Compared to other IR radiations used for thermo-therapy such as IR-C radiation, wIRA is approximated (up to a high degree) to the natural IR-A radiation of the sun, filtered by the water vapor in the atmosphere. Humans are adapted to this radiation during evolution. wIRA can be applied contact-free and thus also to ulcerated lesions without any discomfort for patients. Combining wIRA with a part of the visible spectrum clearly indicates the irradiated target field without influencing heating and allows for real-time temperature monitoring in the treatment field; this is unique in the hyperthermia field. The water bands in the spectrum reduce the risk of thermal skin damage yet supply sufficient energy for effective tissue heating (39–43 °C) up to tissue depths of 26 mm [22].

References

1. Krause R, Stange R. (Hrsg): Lichttherapie. Einführung und Geschichte der Lichttherapie. In: Spuren einer Heliotherapie im Altertum. Berlin, Heidelberg: Springer; 2012.
2. Wikipedia. Stromatolite. Text is available under the Creative Commons Attribution-ShareAlike License.
3. Spectr J. The life of stars and their spectra. Under references: The internal structure of the sun (from the book, Astronomy and Space"), in Greek. Permission by Dr. Margarita Metaxa, a co-author of this book.
4. Wikipedia. Proton-Proton-Reaktion. Text is available under the Creative Commons Attribution-ShareAlike License.
5. Wikimedia Commons. File: EM spectrum.svg. This image comes from the English Wikipedia (Original author: Philip Roman. The file is licensed under the Creative Commons Attribution-Share Alike 3.0.
6. Wehrli C. Extraterrestrial solar spectrum. Davos Dorf: Physikalisch-Meteorologisches Observatorium + World Radiation Center; 1985.
7. Magrathea Informatik GmbH. Erstaunliches und Bekanntes beim Planckschen Strahlungsgesetz. Dollinger J. 2014;2:12.
8. Die Chemie-Schule. Wikimedia Commons. Hydrogen bonding of water molecules 2D. Benjah-bmm27. Public domain; 2007.
9. Die Chemie-Schule. Wikimedia Commons. Hydrogen bonds in water. Original author: Raimund Apfelbach. Public domain; 2010.
10. Bogdan W, Jerzy D. Light absorption by water molecules and inorganic substances dissolved in sea water. Cham: Springer; 2007. p. 11–81.
11. Ramasesha K, De Marco L, Mandal A, et al. Water vibrations have strongly mixed intra- and intermolecular character. Nat Chem. 2013;5:935–40.
12. Libre Texts Libraries. Combination vibrations, overtones and fermi resonances. Davis: University of California; 2020.
13. Cruzan J. xactly.com, Water.
14. Verma PK, Kundu A, Puretz MS, et al. The bend+libration combination band is an intrinsic, collective, and strongly solute-dependent reporter on the hydrogen bonding network of liquid water. J Phys Chem B. 2017;122:2587–99.
15. Tong Y, Kampfrath T, Kramer Campen R. Experimentally probing the libration of interfacial water: the rotational potential of water is stiffer at the air/water interface than in bulk liquid. Phys Chem Chem Phys. 2016;18:18424–30.
16. Vaupel P, Schaible HG, Mutschler E. Anatomie, Physiologie, Pathophysiologie des Menschen. In: 7. Auflage. Stuttgart: Wissenschaftliche Verlagsgesellschaft; 2015.
17. Vaupel P. Blood flow, oxygenation, tissue pH distribution and bioenergetic status of tumors. Berlin: Ernst Schering Foundation; 1994.
18. Xia J, Yao J, Wang L. Photoacoustic tomography: principles and advances. NIH Public Access Electromagn Waves. 2014;147:1–22.
19. Tsai S-R, Hamblin MR. Biological effects and medical applications of infrared radiation. J Photochem Photobiol B Biol. 2017;170:197–207.
20. Wikipedia. Datei. Abbildungsfehler am Hohlspiegel (Katakaustik).svg. The file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported.
21. Vaupel P, Piazena H, Müller W, Notter M. Biophysical and photobiological basics of water-filtered infrared-A hyperthermia of superficial tumors. Int J Hyperthermia. 2018;35:26–36.
22. Piazena H, Müller W, Vaupel P. Glossary used in wIRA-hyperthermia (see Chapter 1, this book).