

MEDICAL AND SCIENTIFIC APPARATUS WITH MICROWAVE THERMAL AND NON-THERMAL EFFECT

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Abstract: Microwave radiation is widely used in medical and scientific applications. Despite its huge occurrence, the microwave effect (on the assumption of interaction between the microwave incident power and the probe or biomass) is not entirely known. The most known effect of the microwave radiation is heating (the thermal effect). However, due the mechanism of interaction between microwave radiation and bio-molecule, the microwave power deposition into the tissue is based on a selective absorption. During a microwave treatment, into the tissue may occur dipolar displacement, free charge current or/and resonant absorption. What makes difference in generating a thermal or non-thermal effect is the microwave incident energy, the local characteristics of the biomass and the way in which the human body is adapting and reacting to the microwave stimulus. This article briefly presents the authors experience in understanding the microwave interaction and use the microwave radiation in designing scientific and medical equipment.

Keywords: microwaves, thermal effect, non-thermal effect, diathermy, hyperthermia, ablation, acupuncture, bioresonance, microwave reactor

1. MICROWAVE INTERACTION WITH THE BIOMASS OR PROBE

Microwaves are non-ionising [1] EM radiations in the frequency range of 300MHz and 300GHz named also centimeter waves (1).

$$\lambda_0[cm] \approx \frac{30}{F[GHz]} \quad (1)$$

where: λ_0 = open space wavelength [cm]
 F = radiation frequency [GHz]

The microwave interaction with the biomass is governed by the permittivity dielectric tensor:

$$\varepsilon = \varepsilon_0(\varepsilon' - j\varepsilon'') \quad (2)$$

where: ε is the body complex permittivity
 ε_0 is the free space permittivity:

$$\varepsilon_0 = 1/c^2 \mu_0 = 1/36\pi 10^{-9} [F/m] \quad (3)$$

$c = 299792458$ [m/s] the light speed

$$\mu_0 = 4\pi 10^{-7} [H/m] \quad \text{free space}$$

magnetic permeability

$$\varepsilon_r = \varepsilon' / \varepsilon_0 \quad (4)$$

ε_r is the relative dielectric constant

The relative dielectric constant (4) characterizes the cell tissue polarization capacity caused by the electromagnetic field

and depends by microwave frequency and tissue specific and temperature [2].

$$\varepsilon'' = \sigma / \omega \varepsilon_0 \quad (5)$$

ε'' is the imaginary part of the complex permittivity (the dielectric loss) indicates the molecule oscillation (translation and vibration behavior) and the ionic and/or dipolar displacements current, caused by the interaction with the microwave field (6) and the local characteristics of the tissue (7) including the tissue shape and vascularisation.

where:

$$\omega = 2 \cdot \pi \cdot F \quad (6)$$

and : ω is the angular frequency [rad/s]

F is the microwave frequency [Hz]

$$\text{and: } \sigma = 2 \cdot \pi \cdot F \varepsilon_0 \varepsilon'' \quad (7)$$

is the tissue electrical conductivity [S/m]

Notice that tissue is not homogenous and the tissue dielectric constant as well the conductivity is variable. Tissue conductivity depends by its intrinsic characteristics, by the microwave radiation frequency and through ε_r by the local body temperature.

While in open space, the microwave wavelength is described by (1), once the radiation penetrates the human body tissue, the wavelength becomes shorter (8).

$$\lambda_b \approx \lambda_0 / \sqrt{\epsilon_r} \quad (8)$$

where: λ_b = body wavelength [cm]

The approximate wavelength variation for two frequently used ISM frequencies at the microwave generator respectively in the human body, are presented in Table1.

Table 1. Open space versus human body wavelength

frequency wavelength	915MHz	2450MHz
λ_0 [cm]	32.7cm	12.2cm
λ_b [cm]	5cm	1.9cm

Note that the wavelength in the human body is comparable with the internal organs dimensions. As higher the microwave frequency as easy to focus the radiation on the damaged organs. However the maximum frequency which penetrates de skin is around 3Ghz, higher frequencies are absorbed in the skin surface. As lower the microwave frequency, as easy to penetrate into the body or probe but much difficult to focus the radiation. The penetration capability is defined by the penetration depth (9), the length measured from the body surface where the microwave power density attenuates with $e = 2.71$

$$d = \sqrt{\frac{2}{\omega \mu_0 \mu_r \sigma}} \quad (9)$$

where: $\mu_r=1$ for a normal human body tissue and μ_0 previously defined at (3).

The characterization of a specific biomass response to the microwave radiation is given by the Specific Absorption Rate (10). SAR expresses the microwaves power absorption per mass unit [3]. For the following analyze it is considered that entire microwave power is transformed in heat. The absorption generated by the microwave power deposition(W) in a volume (V) of the biomass is defined by it's mass and density ($dW/dm = dW/\rho \cdot dV$).

$$SAR = \frac{\sigma}{\rho} E_{rms}^2 [W/kg] \quad (10)$$

where: E_{rms} = root mean square of microwave electrical field

ρ = tissue density [kg/m³]

σ = tissue electrical conductivity [S/m]

SAR is a variable parameter which depends on the microwave applicator (antenna), microwave propagation (wave reflections)

and local characteristics (shape of the biomass, vascularity, body temperature, etc.).

The Pennes approximation (11) to biological heat transfer via diffused conduction and blood convection in a living tissue [4],[5],[6] describes microwave-induced rises in tissue temperature. Equation (11) is neglecting the metabolic heat.

$$\rho c(dT/dt) = SAR + \zeta \nabla^2 T - V_s(T - T_0) \quad (11)$$

where: T = tissue temperature[C]

T_0 = environment temperature [C]

c = tissue specific heat [J/kg K]

ζ = coefficient of heat conduction

$\zeta \nabla^2 T$ = heat conduction term

V_s = product of flow rate and heat capacity of blood

$C_{he} = V_s(T - T_0)$ = convection heat exchange term

The heat conduction term describes a passive phenomenon which takes place slowly in the biological tissues and can be neglected. The convection heat exchange term C_{he} serves to moderate temperature elevation in tissues because heat is transported away from the generating site by the blood [5] and cooled in the capillary vessels. With the comments above, equation (11) becomes:

$$\rho c(dT/dt) = SAR - C_{he} \quad (12)$$

or, taking into account expression (10):

$$\frac{\Delta T}{\Delta t} = \frac{1}{\rho \cdot c} (SAR - C_{he}) \quad (13)$$

where: $\Delta T/ \Delta t$ is the temperature increase rate [°C/s]

Expression (13) represents the key of the temperature rise control into a living tissue. Since SAR is difficult for being measured into a living body, but we can measure the microwave power at the generator output:

$$P = \sigma \cdot E_{rms}^2 / 2 \quad (14)$$

where: E_{rms} = root mean square of the electric field of the microwave radiation. Replacing (14) and (10) into (13) we conclude:

$$\frac{\Delta T}{\Delta t} = \frac{1}{2 \rho c} (E_{rms}^2 - C_{he}) \quad (15)$$

The tissue temperature increase (ΔT) in a microwave thermal procedure is proportional with the microwave power deposition into the

tissue (E_{rms}^2) and the irradiation time (Δt) (assuming deliberately in a false way that tissue is characterized by quasi-constant parameters σ , ρ , c).

The driving system of a microwave generator used for treatments [7] should control the microwave power, the treatment time and the microwave energy deposition with a high resolution. As seen in (15), the effect of a particular microwave power can be equilibrated by the human body reaction (a small microwave power is entirely compensated by the blood flow) and the local effect created by the microwave irradiation becomes non-thermal.

The non-thermal effect can affect the whole body if the microwave power (or whole body average SAR) is small enough to increase the temperature with only about 0.2°C-0.3°C on an average irradiation time of 6 minutes [7]. However the precise threshold value between thermal and non-thermal effect caused by the microwave irradiation is still unknown (Table 2) and the values published in the literature are controversial [9], [10].

Both scientific and medical applications which are using microwave radiations have common elements (fig.1, fig.4), what makes the difference are the compulsory restrictions stipulated by the medical basic and collateral standards [11].

Table 2. Microwave exposure limit in different countries

Exposure type	F [GHz]	Power density [W/m ²]	Average SAR [W/kg]	Country
occupational	0.01-10	50	0.4	EU, Romania
general		10	0.08	
general	0.3-300	5	0.04	USA
general		0.05	0.0004	Russia

2. MEDICAL PROCEDURES USING MICROWAVES

The science of medicine has grown in two directions:

- classical medicine (known as western medicine or scientific medicine) which is healing the physical body using allopathy and a lot of technical procedures (investigation, diagnostics, surgery, radiology, etc.).

- quantum medicine (or new medicine) which action is directed to correct the energetical body (the astral body), healing indirectly the functions of the physical body

The non-thermal effect of the microwave procedures (bioresonance [12] and acupuncture [13]) is intensively used in quantum medicine. Non-thermal microwave medical procedures are using a broad range of extreme high frequencies (EHF: 30GHz-300GHz) and some resonant frequencies with the intrinsic frequencies generated by the human cells and body organs (41.3GHz, 49.12GHz, 51.75GHz, 53.3GHz, 60.12GHz). This concept is based on the coincidence of EHF-radiation frequency with the frequency of relaxation oscillation in some biological molecules. Has been demonstrated [14] that:

- radio-physical resonances of EHF radio-waves with objects exist;
- spontaneous shifts of resonant frequency and low frequency auto-oscillations are observed;
- EHF resonances of biological objects (humans) coincide with those of physical objects (water);
- various liquids and aqueous dispersed media have individual characteristic EHF spectra.

The power level of the incident microwave radiation is chosen in the range of 10μW/cm² for bioresonance and a few mW/cm² up to 2W/cm² for acupuncture and is not able to create any thermal effect on tissue. Most known microwave bioresonance (Cemtech [15]) and acupuncture devices (Milita [16], Yav [17], Magnon, Artsach [18]) available on the market today have been developed by Russian researchers. Another research direction which is using non-thermal effect is the use of high peak power (20KW) EHF pulses (35.27GHz, 100ns), average power of 10-100mW/cm² for anti-inflammatory effects [19].

The thermal effect of the microwaves is used only in classic medicine and is splitting the procedures due to the maximum temperature reached during the treatment in: diathermy, hyperthermia and ablation (or thermotherapy).

Diathermy exerts physical effects by heating the body below 42°C, reflecting closely the general effect of heating: healing various pains [20], treating the acute muscular disease [21], chronic inflammation,

fibrosis or increasing of the sanguineous flux. RF diathermy apparatus are using mostly low frequency ISM band (13.5Mhz, 27.1MHz) but also microwaves (2450Mhz) with output powers between 10W and 500W. A few known diathermy devices on the market today are Celsius TCS, Germany [22] or Thermatur, Ireland [23].

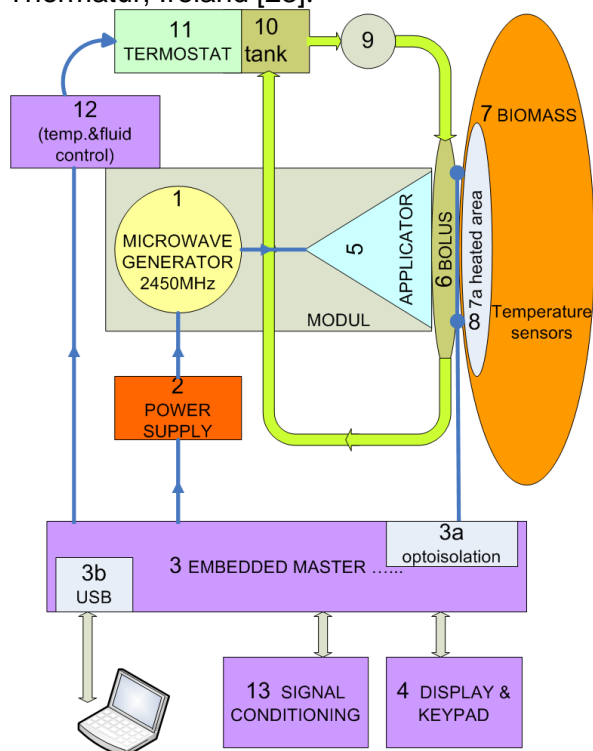


Fig.1. A simplified structure of a hyperthermia installation

Hyperthermia is a physical therapy technique which raises the temperature of a given tissue or of the whole body, between 41.5°C and 45°C and maintains in this range for the treatment period which varies from 30min to 60min [21]. Hyperthermia has been used as medical procedure in oncology since 1975, in addition to radiotherapy, in the management of different tumors [24], [25]. Applying microwave hyperthermia weekly (42 to 72 hours between consecutive treatments) concomitantly with ionizing radiation, results in faster regression rate than ionizing radiation alone. In normal tissue blood vessels dilate on artificially heated, which causes an increase in blood flow through the region and decrease the temperature. In the tumor, pathologic vessels are not able to dilate, by heating some of them collapse, delivered heat is not reduced by blood flow and the intra-tumoral temperature increases. Tumoral cells are finally destroyed by high temperature which causes protein denaturation, those are

destabilize the cell membranes and the cell nucleus [26]. Microwave power generators for hyperthermia are using most of the ISM band frequencies (13.5MHz, 27.1MHz, 433MHz, 915MHz, 2450MHz) and some non-standardized frequencies (8MHz, 140MHz) at high power level (60W to 1200W). A simplified original installation for local hyperthermia (on surface tissues) is presented in fig.1.

The microwave circuit is designed around a microwave generator (1) which comprises a continuous wave (CW) commercial magnetron. The CW magnetron is supplied from an IGBT inverter (2). The applicator (5) is a microwave coaxial antenna at 2450MHz. A medical grade temperature sensor (8) is a component part of the coaxial applicator. Note that any temperature sensor placed in the microwave field, in direct contact with the biomass can be easily overheated, thus creating errors in the temperature measurement process and can burn the patient's skin, this is the reason why non-contact temperature sensors are preferred. An embedded master system (3) is driving the microwave generator power supply (2) and measures the biomass (7) heated area (7a) temperature. Some input/output parameters can be displayed on an alphanumeric LCD display (4) and programmed from a functional keypad and an encoder. An opto-isolated USB (3a) can connect the embedded master with a PC, however connection with the PC is not mandatory during the treatment period. An embedded slave (12) is driving a Peltier-based thermostat (11) which is heating or cooling deionized water in the tank (10). A temperature sensor measures the water temperatures. Warm water or cold water is flowing through the bolus (6) in the fluid circuit, being pumped by the pump (9). The bolus (6) is also an impedance adapting circuit between the applicator (5) and biomass (7) avoiding the free space propagation of the microwave. The free space impedance is 377ohm, while the human body impedance is variable in the range 40-120ohm. The signal conditioning circuit (13) consists in a panic button at the patient hand and a light indicator. The prototype of the microwave generator (MODUL, fig.1), designed and manufactured at the INCDTIM-Cluj Napoca, Romania, can be seen in the lab (fig.2) and mounted on its frame in the hospital (fig.3).

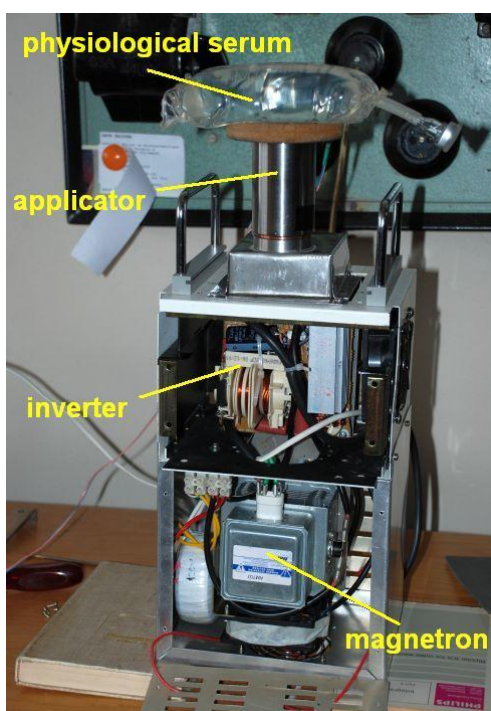


Fig.2. The CW 2450MHz/250W microwave generator for hyperthermia on the test bench, INCDTIM-Cluj Napoca

On the market today, there are a few famous manufacturers of RF and microwave hyperthermia apparatus as BSD USA [27], or Oncotherm Hungary [28]. Those devices are able to perform whole body or regional (including interstitial) hyperthermia procedures, using noninvasive or minimal invasive applicators. None of the hyperthermia devices identified by us on the market are using the non-thermal microwave effect, the essential function of those designs is heating the patient and controls the temperature distribution in the heated tissue.

Microwave ablation is a surgery procedure, used in resection of soft and highly vascularized tissues (liver [29], lung [30], prostate [31], etc.), in endometrial ablation [32] or keratoplasty, by heating the tissues at temperatures of $45^{\circ}\text{C} < T < 100^{\circ}\text{C}$. The high frequency radiation through the antenna displaces the molecules within the tissue. Changes in the energy state of the molecules results in localized rise in temperature. Special configuration of the microwave applicator (needle ablation) can generate plasma between electrodes, used for precisely cutting of the tissue.

The focal heating mechanism of the living tissues has two phases: the first is a direct heat injury phase determined by the amount of energy applied to the tissue, the second is

an indirect injury phase which takes place after the removal of the thermal stimulus (and continues up to 1 to 7 days) and its mechanism is undetermined.



Fig.3. Hyperthermia installation with six axis freedom frame, using the CW microwave generator

Some well-known microwave ablation device on the market are Evident [33], manufactured by Corvidien USA and Microsulis (Femwave), [34] Microwave Endometrial Ablation device running at 9.5GHz, manufactured by Microsulis UK.

3. SCIENTIFIC APPLICATIONS USING MICROWAVES

Differences between a microwave scientific application (fig.4) and a medical one (fig.1) consist mainly in some particularities of microwave radiation interaction with the probe (which can be an organic or inorganic mixture, liquid or solid) into the microwave reaction chamber (5). Due the nature of reaction, the temperature and the pressure inside the reactor can reach extremely high values (200°C , 20atm).

For this reason, a cooling of the microwave reactor chamber could be necessary. Even such reactors are used for green chemistry, device placement in a ventilated area can be indispensable. An EIA232/EIA485 or Ethernet interface (3b) may connect the reactor with a PC, which contain a databank of reactions. The control

system (3), keypad (4), magnetron programmable power supply (2) and microwave generator (1) have very similar destinations with those used in medical devices. The aspect of such microwave reactor [35], designed and manufactured at the INCDTIM-Cluj Napoca, Romania can be seen in fig.5. The possible applications include probe sample preparation, high efficiency isolation of essential oils [36], [37], digesting or just acting as a microwave catalyst.

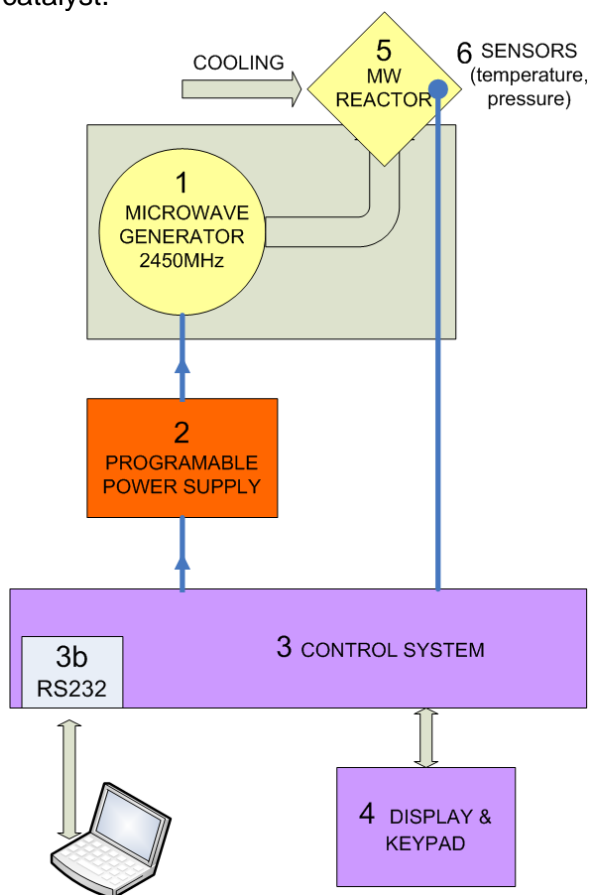


Fig.4. A simplified microwave reactor schematic



Fig.5. Dynamic processing microwave reactor, concept at the INCDTIM-Cluj Napoca

For a specific application, the microwave reactor chamber can be different. In fig.6 is presented a Thin Layer Chromatography (TLC) cavity with a coaxial connection to the microwave generator. In the upper right of the same figure, increased resolution can be observed on chromatograms conditioned in microwaves (A) compared with classic chromatograms (B), [38].

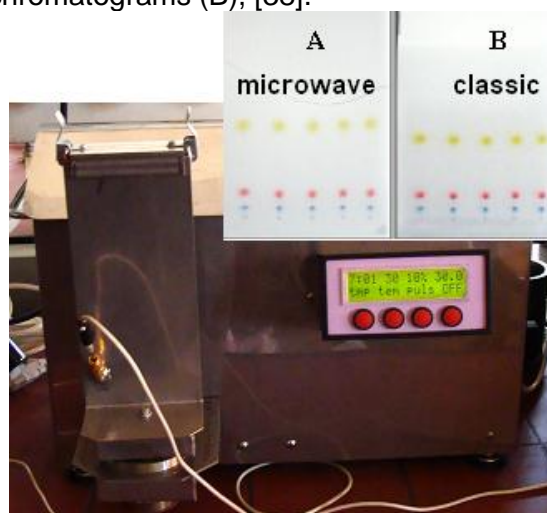


Fig.6. Thin Layer Chromatography using microwaves, concept at the INCDTIM-Cluj Napoca

Some of the producers of microwave reactors (microwave digesters, microwave synthesis, etc) are: Milestone, USA [39], Anton Paar, Austria [40] or Biotage, Sweden [41].

4. CONCLUSIONS

Microwave radiation interacting with living tissue (biomass) or with chemical probes is creating different effects based on the selective absorption mechanism of the probe/tissue. Thermal effect of the microwave radiation is widely used in medical diathermy, hyperthermia and ablation procedures or in chemical microwave digestion and synthesis. Even the thermal effect is quite known, the second phase of the focal heat destruction mechanism in living tissues (which takes place after the complete removal of the microwave thermal stimulus) has an undetermined mechanism. The non-thermal effect of the microwave radiation is a controversy subject, even is widely used in microwave bioresonance and acupuncture for healing various pains and in chemistry on dynamic processing of substance acting as a catalyst.

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