TEMPERATURE CONTROL SYSTEM FOR THERMORADIOTHERAPY FACILITIES

A.M. Fadeev, S.M. Ivanov[1], S.M. Polozov
National Research Nuclear University - Moscow Engineering Physics Institute, Moscow, Russia
[1] and N.N. Blokhin Russian Oncological Research Center, Moscow, Russia
E.A. Perelstein, Joint Institute for Nuclear Research, Dubna, Russia

Abstract

As known, thermoradiotherapy and hyperthermia are widely used to improve the efficiency of cancer treatment.

Whole-body hyperthermia is used to treat metastatic cancer that has spread throughout the body, regional is used to treat part of the body (for instance leg or abdominal cavity). Local hyperthermia permits to heat tumour without overheating of healthy tiisues. It was proposed to use an array of eight independently phased dipoles operating on 100-150 MHz to focus the RF energy in deep-situated volume of 30-50 mm size. But the problem of non-invasive temperature measurement should to be solved for correct operation of the local thermoradiotherapy system. Conventional invasive thermometry devices as thermocouples, thermistors or Bragg optical sensors can not be widely used because of serious risk of the cancer cells transport to healthy tissues. Radiothermometry or acoustic thermometry can not be used for tissues located deeper than 5-7 cm. As known electrodynamics characteristics of tissues are sufficiently depends on temperature. It was proposed to use this effect for active radiothermometry in local hyperthermia. Two opposite RF dipoles can be used as generator and receiver of pick-up signal. It was shown by simulations that such method can be used for thermometry of deep-situated tissues and this method produces high resolution. Results of simulation will present in report.

INTRODUCTION

Hyperthermia is an adjuvant methods of cancer treatment in which tumour temperature is increased to high values (40-44 °C). It is usually used in combination with radiotherapy (thermoradiotherapy, TRT). The most evident approach is using an RF applicator(-s) situated around the patient body. RORC clinical studies demonstrate improving results of treatment by combined using of hyperthermia and radiation for the several tumour localizations. But only applicators for superficial hyperthermia were used in RORC. Common RORC-MEPhI-JINR project is pointed to expand the range of utilizing devices, i.e. using of devices for the regional hyperthermia gives more advantages for an oncological diseases treatment [1-6].

It was shown by many sets of simulations and experiments that such termoradiotherapy facility can provide the effective RF power focusing by means of amplitude and phase control for each applicator and effective local hyperthermia can be provided. As one example, the array of dipoles operating on 150 MHz with aperture diameter of 60 cm can provide RF power focusing wherever of patient body with spot diameter about 30 mm. A 450 MHz system can be used for hyperthermia of head and neck tissues with heated volume size of 15-20 mm.

Thermometry into heating volume is one of the major hyperthermia tasks. It is more difficult for deep-situated tissues. It is possible to use invasive or contact thermometry systems as thermistors and thermo-couples for deep-situated tissues and tumours. Russian hyperthermia protocol permits installation of thermocouples inside the patient body. But this causes pain and temperature probe can transport tumor cells to the healthy region of the patient body. European hyperthermia protocol forbids installation any temperature probes inside the patient body. They prefer to simulate any radiation process with phantoms. Moreover noninvasive thermometry of human tissues is important for other cases. It is suggested to determine tissues temperature by means of measurements effects that could be observed during heating. Optical fiber sensors based on Bregg grids became more popular last years. The measured parameter as temperature or mechanical displacement is coverts to the length of the light shift. But all of such sensors (thermo-couples, thermistors or optical fiber sensors) provide only invasive temperature measurement. Noninvasive control is possible by using of the magnetic resonance imaging (MRI) as it is proposed and realized by BSD Medical Systems (now Pyrexar Medical). But such way has serious difficulties and the price of MRI system is higher than the same of the hyperthermia system. Acoustic thermometry is one of new technologies. 2D and 3D temperature distributions were successfully imaged by means of acoustic thermometry experiments. But such technique can be used only for tissues located not deeper than 3-5 cm (for mammography as an example). Well-known radiothermometry (RTM) also can be used for deep-situated tissues. As known, the specific heat release of tumour is directly proportional to its growth velocity. More fast growth tumours will be "hotter" and will be brighter on the thermograph. The possibility to find the fast growth tumours is an unique advantage of the RTM. Main sufficient disadvantage is inherent as for acoustic thermometry: RTM can not be used for the deep suited tissues. The depth of temperature anomaly localization will not be greater than 3-7 cm depending of the tissues humidity.

ISBN 978-3-95450-181-6

THERMOMETRY IN PROCESS OF THE THERMORADIOTHERAPY

As known dielectric properties of the tissues (complex dielectric permittivity and tangent of the dielectric loses) depend of temperature. It is suggested to determine tissues temperature by means of measurements effects that could be observed during heating process. Thus dielectric properties of the human tissues sufficiently varies with temperature increasing (fat tissue and skin are not heated during hyperthermia with the phased array). This thermometry system could be used as addition to the other regional or local hyperthermia facilities. For example, the real part of dielectric permittivity of the muscle tissue or tumour tissue growths by 0.2-0.5 per 1 degree (absolute value is 70-100). It leads to the special absorption rate variation and to RF power scattering modification in tissues. Such variation can be registered. Detail review of experimental data, a number of theoretical models and results of numerical simulations are given in [7-9] for temperature dependences of electrodynamics characteristics for different tissues and organs. Two examples of real ε' and imaginary ε'' components of the complex dialectical permittivity $\varepsilon=\varepsilon'-i\varepsilon''$ are shown in Figure 1. Dependences are modeled for muscle tissue and liver using data from [8-9]. The operating frequency is 150 MHz. It is clear that such dependences are close to linear for temperature range 36-43°C which is used for thermoradiotherapy. The analyses of experimental and simulated data form [7-9] shows that for operating frequency of 150 MHz absolute values of ε' and ε'' are close for all tissues. Only dielectric properties of skin and fat tissues differ very significantly.

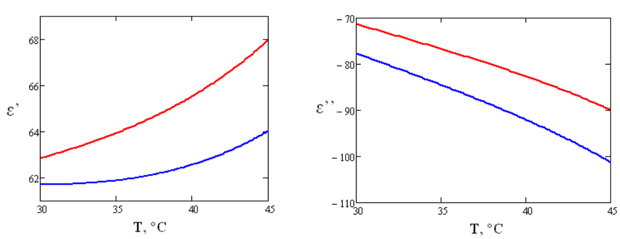

Figure 1: Dependences of real ε' and imaginary ε'' components of the complex dialectical permittivity for muscle tissue (blue) and liver (red). The operating frequency is 150 MHz.

Each dipole antennae feeds independently in the hyperthermia facility proposed in [1-6]. Each feeding channel includes RF circulator (see Fig. 2) to prevent the back wave penetration to the other feeding channels. Such system with minor modifications can be also used for thermometry. In the temperature measurement regime two feeding channels (RF input #1 and #5 in Fig. 2) will switch to low RF power regime and the feeding of all other dipoles turns off. The output of the circulator directs the transmitted back wave to the band-pass filter and further to the measuring PIN-diode. PIN-diode measures the time dependence of the RF power flux for further A/D conversion. Digital signal processes by the especially developed Fourier analyses code and time dependences of Fourier coefficients define. Current spectral series compares with "non-perturbed" signal which was previously defined for not heated patient body. Proposed radiothermometry technique differs very sufficiently from the conventional one: i) the thermometry system is combined with hyperthermia one and dipole antennae are used both for heating and thermometry; ii) the thermometry can be realized for deep situated tumours and tissues; iii) the noninvasive thermometry can be realized and the active tissues scanning can be used for the 2D temperature imaging.

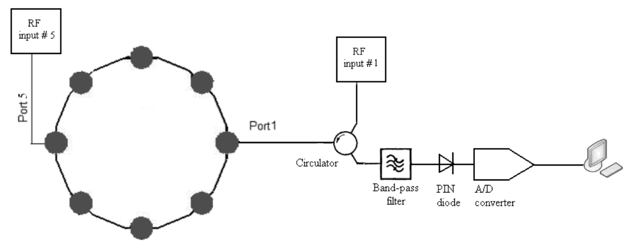

Figure 2: The scheme for measurement and analysys of the transmitted signal.

The simulation of the heating process with temperature control was done to verify the proposed thermometry technique. To define the spectral distribution of the transmitted signal as the function of temperature we do the fast Fourier analysis by the especially designed code. The main signal harmonic amplitude was controlled and the temperature distribution and its time dependence were calculated. The TRT facility was developed to heat only limited volume inside the patient's body. Only characteristics of such local area will influence to the transmitted signal. Its harmonic distribution and temperature control will be also provided for local volume where heating is taking place.

Numerical simulations show that the amplitude of the main Fourier harmonic of the transmitted signal depends of the temperature linearly. The analysis was done using the experimental and simulated data form [7-9] for the operating frequency of 150 MHz. The simulation model is shown in Figure 3, it includes voxel model of the human body with a number of tissues and organs. The dielectric characteristics of tissues were varied during simulation with the temperature increases. The temperature distribution is also shown in Figure 3. The detected transmitted signal is shown in Figure 4. Such detected signal expands to the Fourier series and its coefficients are compare with the "base" distribution which was done and safe for non-perturbed (hot heated, T=37ºC) model. It is clear from Figure 4 that the main signal harmonic amplitude depends vs. temperature linearly. Such result simplifies the back problem of the temperature reconstruction for heated volume.

About 90 % of RF power absorbs by patient body while local or regional hyperthermia as it was shown by numerical simulation. The RF power necessary for effective treatment is up to 100 W/dipole for facility

ISBN 978-3-95450-181-6

proposed in [1-6]. The simulation of the heating process with temperature control shows that for the first Fourier harmonic of the transmitted signal the variation is about ~10^{-3} form coefficient value for the local hyperthermia and ~10^{-2} for the regional one. Temperature increasing range is about 37-43°C. It is clear that the transmitted power measurement accuracy should be better than 100 µW (if measurement signal power is ~1 W). The accuracy of the temperature measurement for the local heated volume will be better than 0.3°C due to such RF power accuracy measurement. Such result is better than for conventional radiothermometry and close to tolerance for invasive thermo-couples or thermistors. The process of local thermoratiotherapy takes 15-30 minutes usually and it is quite enough to measure the temperature 1-3 times/minute.

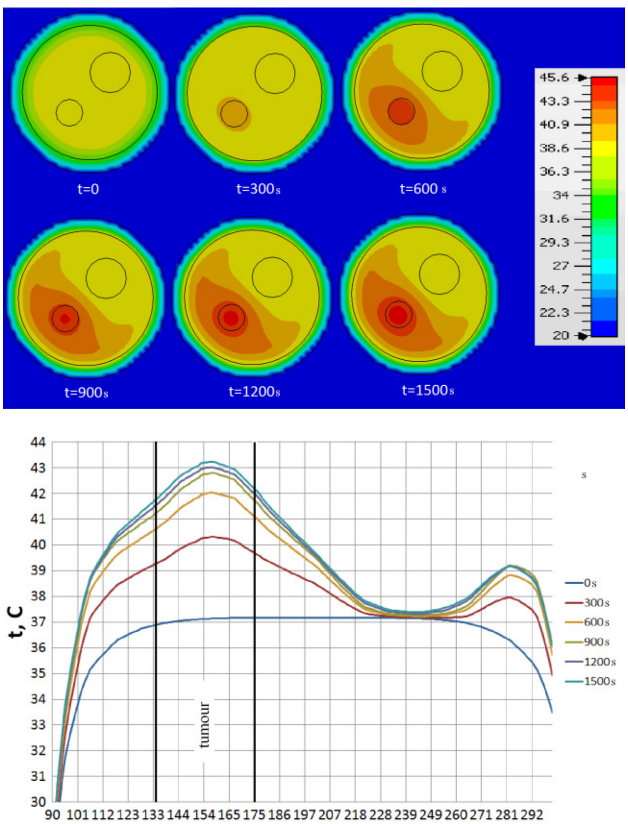

Figure 3: Temperature distributions in tissues for a set of times after termoradiotherapy start: cross-sections of tissue equivalent model (top) and distributions along of the axe pass though centers of two opposite dipoles.

CONCLUSION

It was shown that modified active radiothermometry technique can be used for temperature control during the thermoradiotherapy of the deep-situated tumours. Dipole antennae of the TRT facility can be used both for heating and for temperature measurement. The accuracy of the temperature measurement for the local heated volume will be better than 0.3°C with low (~1 W) measuring signal value.

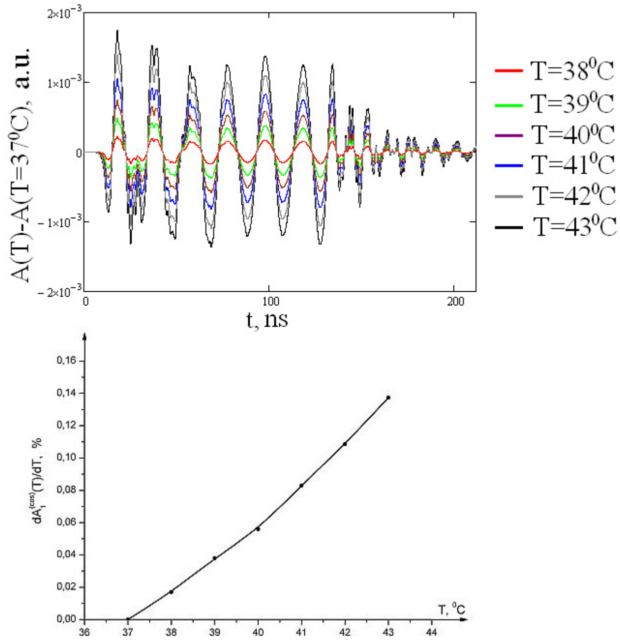

Figure 4: Temperature dependence of the difference (a.u.) of transmitted signal amplitudes for current and “base” (T=37ºC) temperatures into the heated volume (top) and the temperature dependence of the first Fourier harmonic amplitude.

REFERENCES

[1] Ivanov S.M. et al., Problems of Atomic Science and Technology. Series: Nuclear Physics Investigations, 3 (79), 191-194 (2012).
[2] Fadeev A.M. et al., Proc. of RuPAC’12, 521-523 (2012).
[3] Polozov S.M. et al., Proc. of RuPAC’12, 524-525 (2012).
[4] Ivanov S.M. et al., Problems of Atomic Science and Technology. Series: Nuclear Physics Investigations, 6 (88), 220-224 (2013).
[5] Fadeev A.M. et al., Proc. of RuPAC’14, 240-242 (2014).
[6] Fadeev A.M. et al., Journal of Physics: Conference Series, 747, 012076 (2016).
[7] C. Gabriel, S. Gabriel, E. Corthout, Phys. Med. Biol., 41, 2231–2249 (1996).
[8] S. Gabriel, R.W. Lau, C. Gabriel. Phys. Med. Biol., 41, 2251–2269 (1996).
[9] S. Gabriel, R.W. Lau, C. Gabriel. Phys. Med. Biol., 41, 2271–2293 (1996).

ISBN 978-3-95450-181-6