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20

Fiber Optics for Thermometry in Hyperthermia Therapy

Mario Francisco Jesús Cepeda Rubio,
Arturo Vera Hernández and Lorenzo Leija Salas
Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional,
Department of Electrical Engineering/Bioelectronics
Mexico

1. Introduction

A review of electromagnetic hyperthermia ablative therapies, a temperature measurements during microwave ablation using optical fiber temperature sensors and a fiber optic temperature sensor developed for a hyperthermia laboratory are summarized in this chapter. Hyperthermia also called thermotherapy or thermal therapy is a type of cancer treatment in which body tissue is exposed to high temperatures. All methods of hyperthermia include transfer of heat into the body from an external energy source and are currently under study, including local, regional, and whole-body hyperthermia. The application of heat to treat patients with a malignant tumor is not a novel concept. The Edwin Smith papyrus explains the topical application of heated metallic implements or hot oil that were used approximately 5000 years ago to treat patients with tumors (Izzo et al., 2001). Local hyperthermia is used to heat a small area. It involves creating very high temperatures that destroy the cells that are heated. Research has shown that high temperatures can damage and kill cancer cells, usually with minimal injury to normal tissues (van der Zee, 2002). By killing cancer cells and damaging proteins and structures within cells, hyperthermia may shrink tumors (Hildebrandt et al., 2002). Numerous clinical trials have studied hyperthermia in combination with radiation therapy and/or chemotherapy. Many of these studies, have shown a significant reduction in tumor size when hyperthermia is combined with other treatments (Wust et al., 2002). Otherwise, ablation or high temperature hyperthermia, including lasers and the use of radiofrequency, microwaves, and high-intensity focused ultrasound, are gaining attention as an alternative to conventional surgical therapies (van Esser et al., 2007). Each of these techniques works differently, the objective is to heat tissue to a temperature 50°C above to destroy cells within a localized section of a malignant tumor. Frequently, temperature monitoring during thermal therapy has been achieved using interstitial thermocouples, thermistors, or fiber optics probes. Fiber optics technology should exploit one or more of electromagnetic immunity, noninvasiveness, chemical immunity, small size, or the capacity for distributed measurement. Fiber optic thermometers are used when electrical insulation and EMI immunity are necessary. The most relevant application involves tissue-heating control during microwave ablation (MWA) or radiofrequency ablation (RFA) hyperthermia therapy for cancer treatment (Mignani & Baldini, 1996).

1.1 Radiofrequency ablation

RFA works by converting radiofrequency waves into heat through ionic vibration. Alternating current passing from an electrode into the surrounding tissue causes ions to vibrate in an attempt to follow the change in the direction of the rapidly alternating current. It is the ionic friction that generates the heat within the tissue and not the electrode itself. The higher the current, the more vigorous the motion of the ions and the higher the temperature reached over a certain time, eventually leading to coagulation necrosis and cell death. The ability to efficiently and predictably create an ablation is based on the energy balance between the heat conduction of localized radiofrequency energy and the heat convection from the circulation of blood, lymph, or extra and intracellular fluid. The amount of radiofrequency produced heat, is directly related to the current density dropping precipitously away from the electrodes, thus resulting in lower periphery temperatures. The goal of radiofrequency ablation is to achieve local temperatures that are lethal to the targeted tissue. Generally, thermal damage to cells begins at 42°C; and once above 60°C, intracellular proteins are denatured, the lipid bilayer melts, and irreversible cell death occurs (Simon et al., 2005).

1.2 Microwave ablation

Water molecules are polar; the electric charges on the molecules are not symmetric. The orientation and the charges on the atoms are such that the oxygen side has a negative charge, and the hydrogen side of the molecule has a positive charge. When an oscillating electric charge from microwave radiation interacts with a water molecule, it causes the molecule to flip. Microwave radiation is specially tuned to the natural frequency of water molecules to maximize this interaction. As a result of the radiation hitting the molecules, the electrical charge on the water molecule flips back and forth 2–5 billion times a second depending on the frequency of the microwave energy. Temperature is a measure of how fast molecules move in a substance, and the vigorous movement of water molecules raises the temperature of water. Thus, electromagnetic microwaves heat matter by agitating water molecules in the surrounding tissue, producing friction and heat, thus inducing cellular death via coagulation necrosis (Goldberg & Gazelle, 2001).

2. Fiber optics thermometer

One of the first commercial fiber optic temperature probe was a fluorescence-based temperature sensor introduced in the early 1980s by the Luxtron Corporation of Mountain View, CA. Successors to these sensors are commercially available and are effective, approach to solving measurement problems (Culshaw, 1999). These include monitoring temperature patterns, examining temperature distribution in power transformer oils, and similar areas where the issue is the operation of a reasonably precise temperature probe within very high electromagnetic fields. In such circumstances, a metallic temperature sensor either distorts the electromagnetic field significantly or is subjected to very high levels of interference, producing spurious evaluations. Other applications sectors exploit the small size or chemical passivity of the device, including operation within corrosive solvents or examination of extremely localized phenomena such as laser heating or in determining the selectivity of radiation and hyperthermia treatments.

2.1 Fiber optics for thermometry in hyperthermia

Temperature probes that employ optical fibers were introduced for clinical hyperthermia treatment in the 1980s. Clini-therm Corporation, Dallas, TX founded in 1978 (no longer in business), at that time the company was working to develop and manufacture a system for hyperthermia therapy. The system incorporates fiber optic temperature probes which are inserted into a malignant tumor and surrounding healthy tissue through catheters. The probes detect changes in temperature during hyperthermia treatment.

(Vaguine et al., 1984) developed another probe. It uses a small crystal of the semiconductor gallium arsenide (GaAs) whose optical absorption at a specifically chosen wavelength is sensitively related to the crystal's temperature. The amount of optical signal returned after passage through the sensor may be detected and electronically translated, after calibration, into an indication of the probe's temperature. The system has up to 12 temperature sensors which are packaged in two basic probe configurations: a single-sensor probe with a length of 1.2 m and a diameter of 0.6 mm; and a four-sensor linear array probe with a length of 1.2 m, diameter of 1.1 mm, and spacing of 1.5 cm between adjacent sensors.

(Katzir et al., 1989) reported a fiber optic radiometer system, which is based on a nonmetallic, infrared fiber probe, which can operate either in contact or noncontact mode. In preliminary investigations, the radiometer worked in a strong microwave or radiofrequency field, with an accuracy of ± 0.5°C. The fiber optic thermometer was used to control the surface temperature of objects within ± 2°C.

(Wook et al., 2009) reported a measured temperature distribution using the infrared optical fibers during radiofrequency ablation. Infrared radiations generated from the water around inserted single-shaft plain electrode are transferred by the three silver halide optical fibers and are measured by a thermopile sensor array. Also, the output voltages of the thermopile sensor array are compared with those of the thermocouple recorder. It was concluded that is expected that a non-contact temperature sensor using the infrared optical fibers can be developed for the real time temperature monitoring during RFA treatments based on the results of this study.

Intelligent Optical Systems, Inc., has reported in 2009 an Optical Fiber Temperature (OFT) probe that will provide 10 points of high-resolution temperature data in a single fiber. The OFT probe is an alternative to thick bundles of arrayed single point temperature. According to the company, this new probe will provide a realistic, cost effective, and efficient technique for distributed temperature monitoring and profiling in treated tissues, and use of the OFT probe can reduce complications as a result of excessive heat exposure and damage to the healthy tissue surrounding a tumor. As microwave hyperthermia becomes increasingly popular for the treatment of benign prostatic hyperplasia and other benign or malignant tumors. The OFT provides multipoint and self-calibrating temperature sensing. Measures tumor temperatures at multiple points along a 5 to 10 cm sensor length, with the ability to pinpoint target areas within 0.5 cm. Monitors these temperatures over a large range, including 35°C to 55°C range, with a 0.1°C temperature resolution. Readily interfaces with clinical hyperthermia catheters because of its size (0.25mm thick) and thus will be adaptable to a variety of clinical conditions.

(Saxena & Hui, 2010) reported a polymer-coated fiber Bragg grating (PFBG) technology that provides a number of FBG thermometry locations along the length of a single optical fiber.

The PFBG probe was tested in an environment designed to approximate the microwave exposure that might be encountered during clinical hyperthermia treatments. According to the authors, this offers an enabling alternative to either scanning or bundled single point temperature probes for distributed thermometry in clinical applications.

3. Fiber optics thermometry system for a hyperthermia laboratory

In this section, we present a fiber optic temperature sensor developed for a hyperthermia laboratory. Many benefits coming from hyperthermia depends on the ability to induce and to measure high temperatures locally. The heating is carried out via local irradiation of energy, mainly by means of ultrasonic or electromagnetic waves. To be able to manage the irradiation parameters it is necessary to know the temperature to which the radiated tissue rises, that makes practically indispensable to have a highly reliable system of temperature measurement. The measurement of temperatures is carried out with thermometry systems that can be invasive, or non invasive. The use of the conventional sensors (thermistors, thermocouples, etc.) it is not satisfactory in some applications, just as it is the case of the therapies for hyperthermia with microwaves. This is due to that currents and voltages are induced by electromagnetic interference in the metallic elements and a self-heating by induction appears. Both factors produce erroneous readings as a result in the measurements when using these sensors. When these conditions are presented it is necessary to build sensors denominated, as non-disturbing electromagnetic field, like those based on optical fibers. Among them we find fluorescent sensors, interferometric sensors, those based on the variation of intensity caused by absorption or reflection and the evanescent sensors. At the present time, there are in the world diverse laboratories dedicated to the experimental investigation in hyperthermia, where the electromagnetic radiation is used inside a controlled and safety ambient. In the Section of Bioelectronics of the CINVESTAV-IPN there is an automated laboratory (Chong et al., 2000), in which controlled radiation experiments with microwaves are carried out in the interval from 900 MHz to 8 GHz and pulsating wave ultrasound at 1 MHz. This radiation has an impact on a biological tissue substitute material, where heating is obtained by the interaction of radiation with the radiated material. The experiments are carried out inside an anechoic chamber to avoid the external electromagnetic interferences and at the liberation of the energy radiation to the environment. The thermometry system that is described is part of this automated laboratory (Pennisi et al., 2002). This system measures the temperature inside the phantom, which is heated through the electromagnetic and ultrasonic fields radiations that are being carried out.

3.1 Methodology

The system can be divided in four parts: the stage of temperature measurement using optical fiber sensors and the analog signal conditioning; the stage of automated positioning of the temperature sensors inside the phantom; the communication and control stage using two personal computers; and a general software for the visualization of the temperature distribution inside the phantom. Figure 1 shows a block diagram of the system.

3.1.1 Temperature sensor

This model is an approach based on the theory of the weakly guiding fibers, and don't take into account the length of the sensor. However, we can see that the experimental results
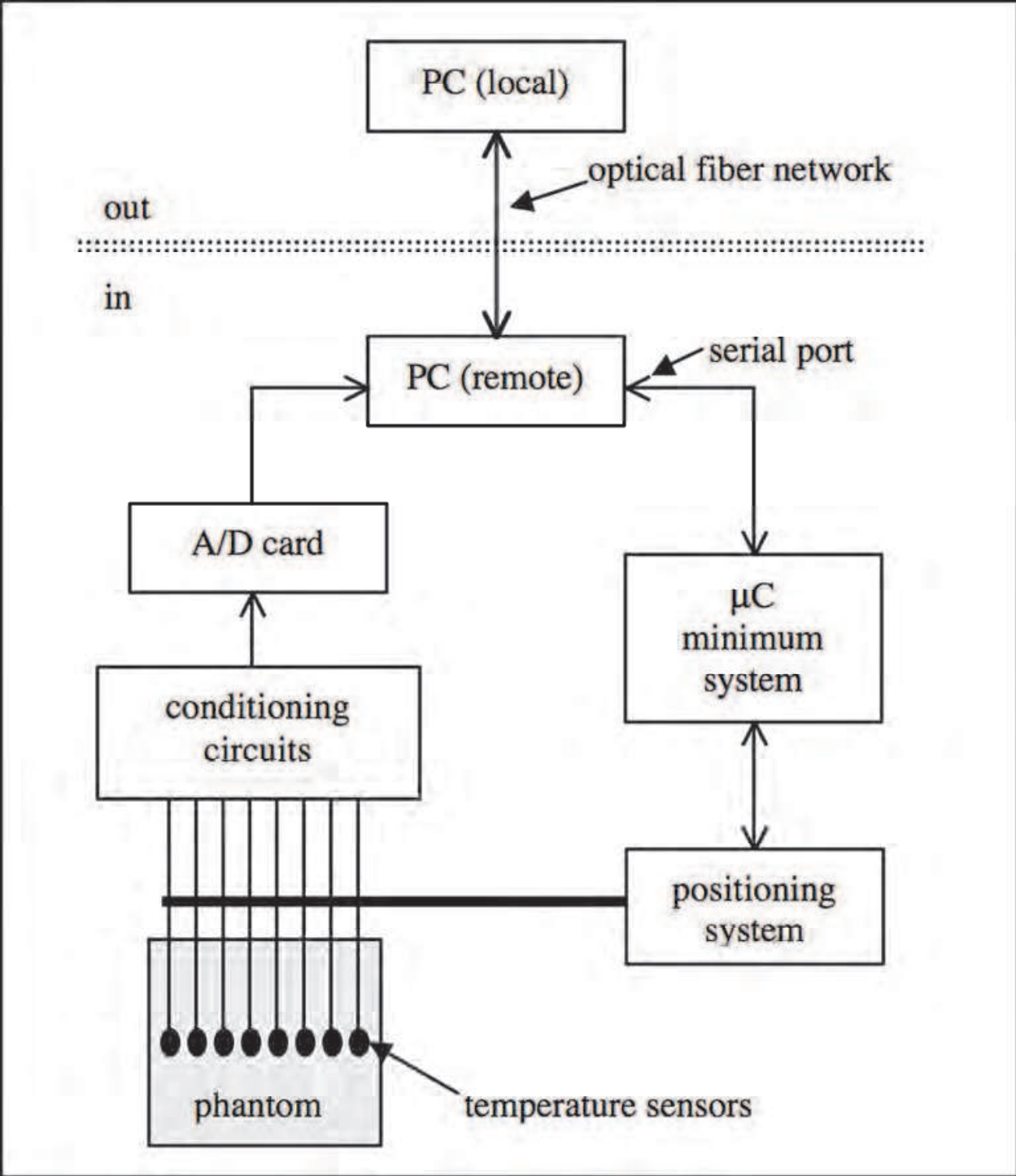
Fig. 1. Diagram of the hyperthermia automated laboratory. In the inner of the anechoic chamber, a PC controls the temperature sensors and the positioning system. A PC located outside the chamber for the visualization of the temperature distribution.

match with the response predicted by the model. Assuming that there is an allowable power flow in both core and cladding, the combined fiber power flow is:

$$P = P_1 + P_2 \text{ (Watts)} \tag{1}$$

where the subscripts 1 and 2 refer to the core and cladding respectively. The ratio of optical powers in core and cladding is:

$$\frac{P_1}{P_2} = \frac{3}{4} N_m^{1/2} - 1 \tag{2}$$

where N_m, represents the total number of free-space modes accepted and transmitted by a step-index fiber. The number of modes is related with the so-called v value by the relationship:

$$N_m = \frac{1}{2} v^2 \tag{3}$$

The v value, sometimes referred to the normalized frequency, is an important fundamental fiber property, because it contains the most important fiber parameters, and is defined by:

$$v = 2\pi \left(\frac{a_1}{\lambda} \right) \left(n_1^2 - n_2^2 \right)^{1/2} \tag{4}$$

where a_1 is the fiber core radius, λ is the free space wavelength of operation and n is the refractive index. The normalized power at the end of the fiber is then:

$$P_{norm} = 1 - \frac{P_2}{P} = 1 - \frac{2\sqrt{2}}{3\pi \left(\frac{a_1}{\lambda} \right) \left(n_1^2 - n_2(T)^2 \right)^{1/2}} \tag{5}$$

From the latter expression, we can see that the power transmitted along the fiber is dependent on the temperature, with an inverse square root relationship. Due to the refraction index wavelength dependence, we have evaluated three different wavelengths for the sensor operation (660 nm, 850 nm and 1300 nm), as well as several different types of oils, with a slightly different refraction index. For our range of interest the best results we have obtained were with vegetable oils, operating in the infrared range. The sensor was fabricated using a multimode patch-cord with ST connectors on both ends, which is commercially available. First, the patch-cord is divided in halves. A 30 mm portion of jacket and plastic buffers are mechanically removed from both ends. After that, a 20 mm glass tube with an external diameter of 1.1 mm is introduced through one of the ends, and both ends of the fiber are joined together with a fusion splicer (RXS-X74). Then the fiber without buffer of this portion is treated with an acid, to remove partially the glass cladding. The acid attack is stopped when the transmitted power falls 30% from its initial value. The glass tube is then located in the central part of the fiber and is filled with the oil. Finally, both ends of the glass tube are sealed with epoxy glue. Figure 2 shows a detailed outline of the probe described above.

The basic setup is showed on Figure 3. There is a lightwave multimeter (HP 8153A) configured with an optical source module (Hp8155IMM) and a power sensor module (HP
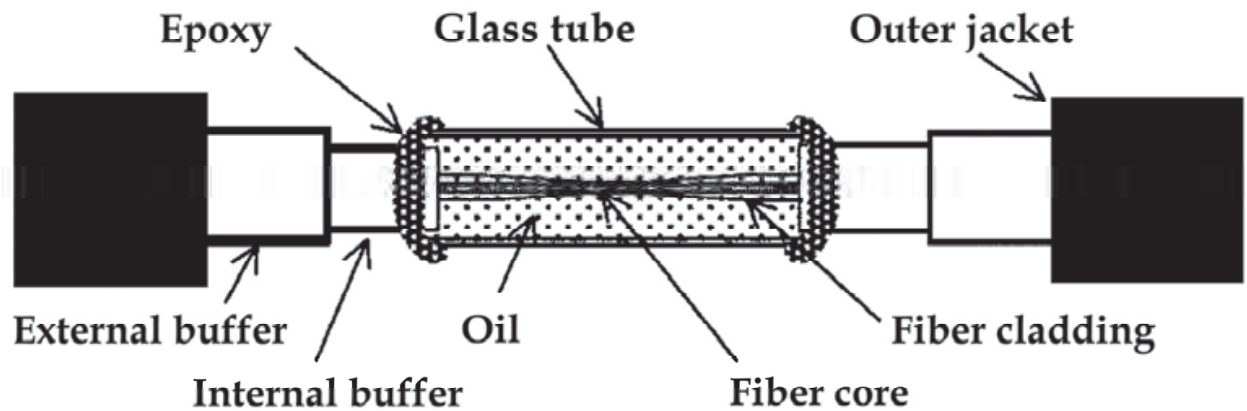
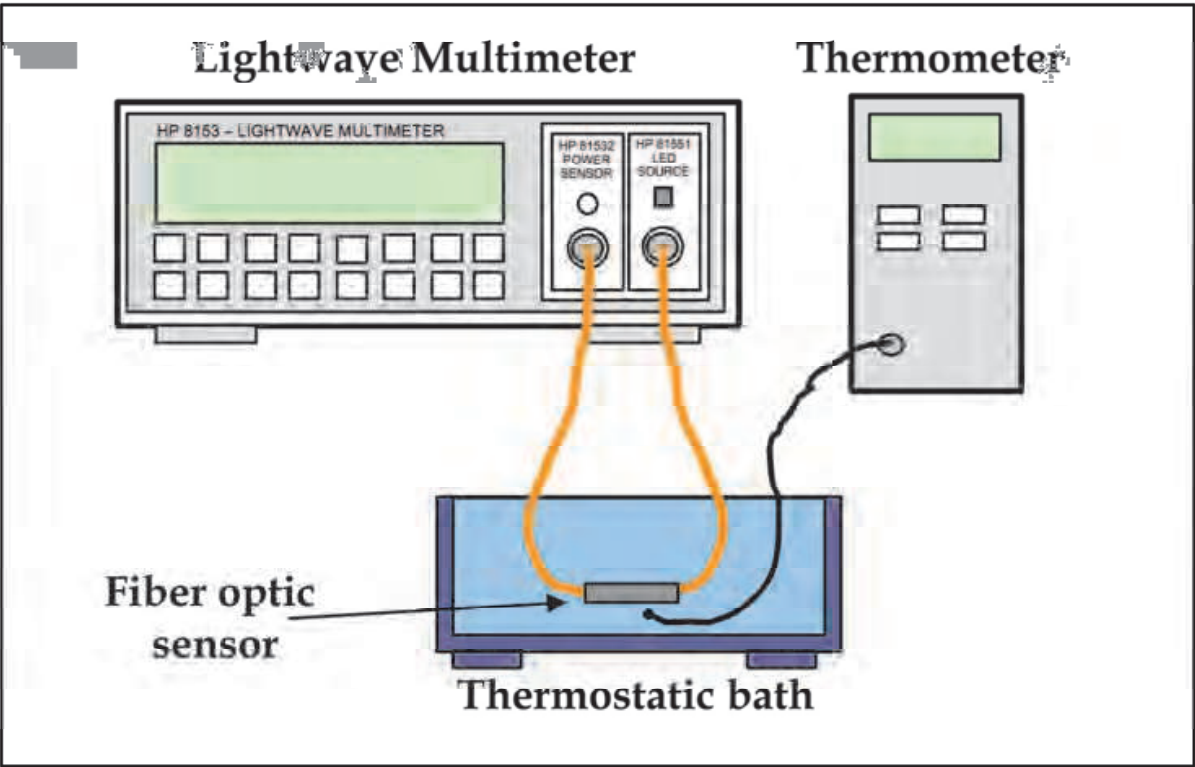Fig. 2. Detailed outline of the constructed sensor (not in scale).

Fig. 3. Experimental setup.

81532A). The stability of the source was evaluated, and was +0.03 dB in a 6 h interval. The fiber optic sensor is connected between the source and the power sensor, and is immersed in a thermostatic bath. The wavelength of operation selected is 850 nm.

3.1.2 Positioning stage

This stage is constituted by a personal computer (PC), a microcontroller and a PC controlled automated positioning system. The PC is IBM compatible. It sends the data that correspond to a position selected by the user toward the minimum system. This PC is located inside the anechoic chamber and it is externally operated through an optical fiber communication system. The communication between the PC and the minimum system is carried out through the communications port COM1. The temperature sensors are displaced in an axis through the

phantom by means of an automated positioning system. Two DC motors controlled by the minimum system by means of the feedback signal that provides an optical encoder impel this. The maximum lineal travel distance is of 35 cm, with a resolution of 2.5 mm. The physical construction of the positioning system is built on a square base of acrylic of 65 x 120 cm of external area, of 1 cm thick. Bars of Nylamid were also used for support. The used materials minimize the interaction with the electromagnetic fields that could be present.

3.1.3 Communication and control stage

The communication system is based on the use of two IBM compatible computers, one of them inside the anechoic chamber (remote) and the other one in the exterior (local). The communication between both computers was carried out through an optical fiber cable; the local PC operates the remote PC. The local PC controls all the equipment inside the chamber and captures all the acquired information. An optical fiber based net card was used to communicate the two computers (3C905B-FX(SC), 3Com 100Base-FX). It possesses a speed of transmission of 100 Mbps. The protocol used to communicate both computers was the TCP/IP. The package used for the communication was the Remote Administrator v2.0, which allows control all the devices and programs of the remote computer from the local computer. The analog signals coming from the eight conditioning circuits were digitized by means of a 12 bits analog to digital card (Lab PC-1200 A/I, National Instruments) that is installed in the remote computer. The communication system is based on the use of two IBM compatible computers, one of them inside the anechoic chamber (remote) and the other one in the exterior (local). The communication between both computers was carried out through an optical fiber cable; the local PC operates the remote PC. The local PC controls all the equipment inside the chamber and captures all the acquired information.

3.1.4 Visualization software

Software was developed in the LabWindows CVI programming language (National Instruments). By means of this software the user can control all the controllable devices that conforms the automated laboratory. Data like the radiation time and frequency, the distance between the radiator and the phantom, the quantity of temperature measurements in a plane of the phantom, the quantity of phantom mappings, sensor thermal response time, the elapsed time between each temperature mapping, among other, should be provided by the user. Once the experiment begins, the laboratory operates automatically and allows the user to visualize the results obtained in each temperature mapping. In Figure 4 the main screen of the program is shown.

3.2 Results

Calibration of the sensor was done using a thermostatic bath and a thermocouple thermometer with an accuracy of 0.1"C (TES-1310). Several calibration curves in different days were taken for the sensor, as shown in Figure 5. With these curves we evaluated the repeatability and the stability of the sensor. We also evaluated the thermal time constant of the sensor, resulting in a value of 1.9 s. As we see, the transmitted power increases with the temperature. While the temperature increases, the refraction index of the cladding decreases in a linear way. At low temperatures (below 5"C), the refraction index of the oil is higher than the refraction index of the core, and no power is transmitted through the fiber, because
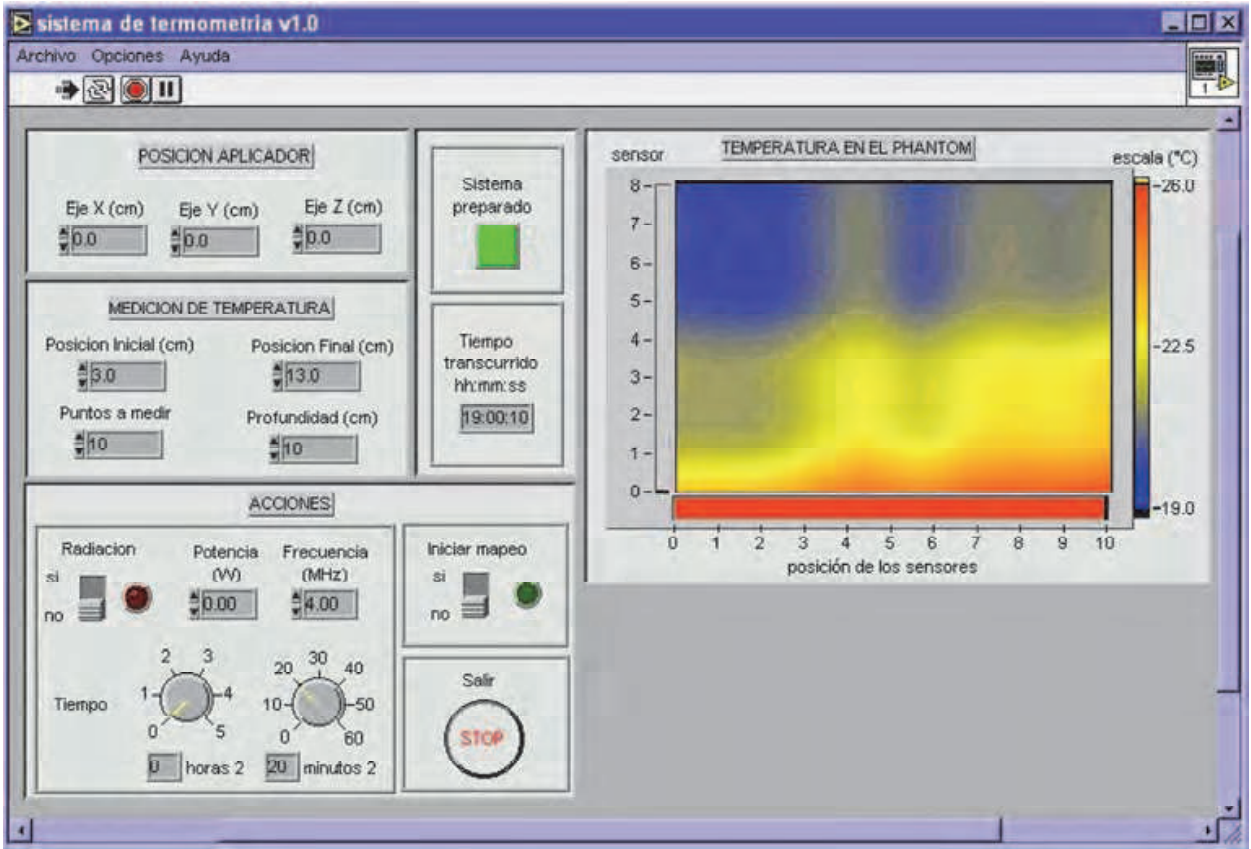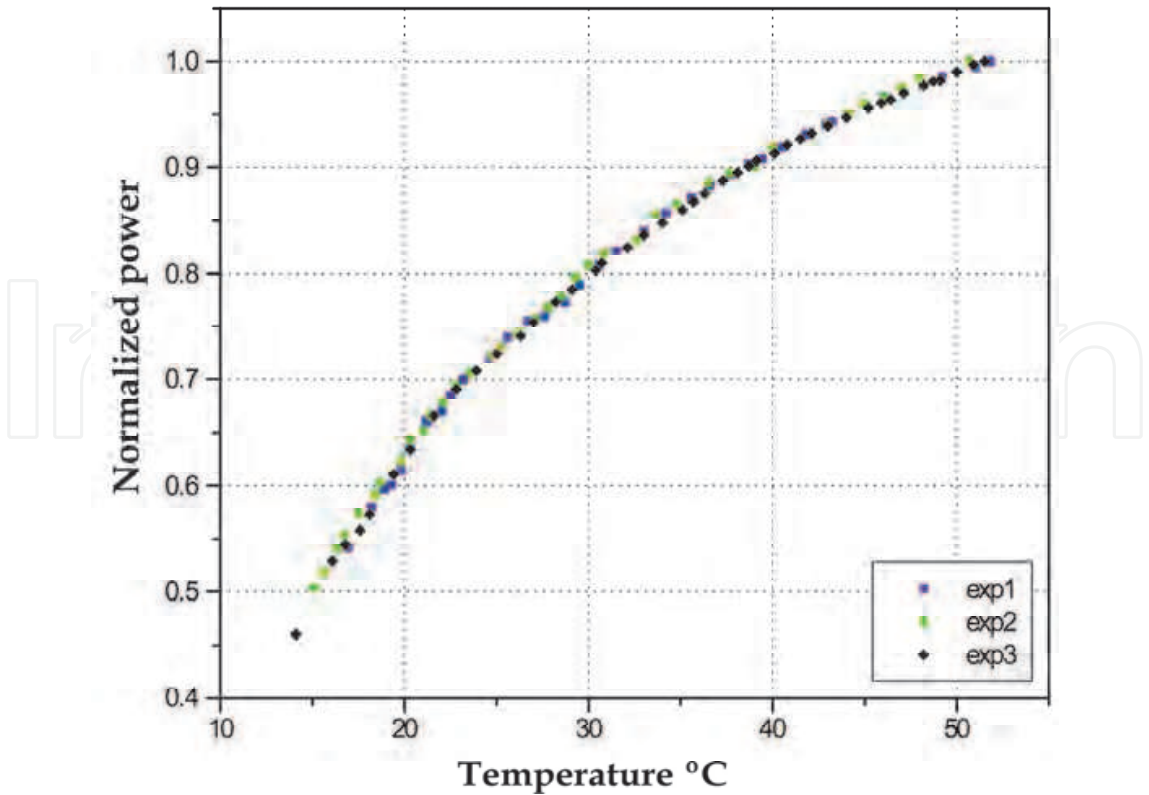
Fig. 4. Software main screen.

Fig. 5. Calibration curves for three experiments.

waveguide conditions are not satisfied. As the refraction index decreases the power transmitted increases, due to the increasing number of guided modes in the fiber. When the oil index equals the refraction index of the cladding, the transmitted power reaches a maximum value, and the curve shows a saturation effect. The sensor performance using microwaves was tested using a domestic microwave oven that operates at 2.45 GHz. The experimental setup was similar to the previously described. Instead the thermostatic bath, we have used the microwave oven, to heat water inside a plastic container. Figure 6 shows the achieved results, compared with a calibration curve obtained with the thermostatic bath.
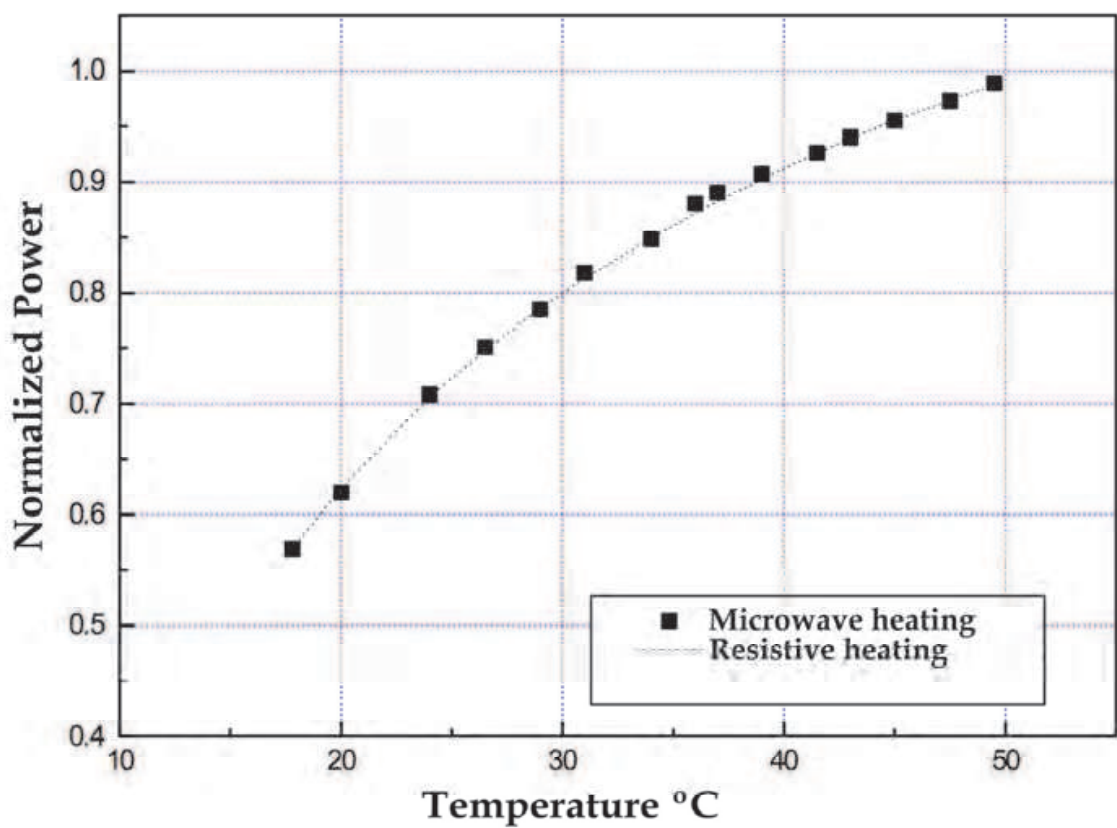
Fig. 6. Calibration curves for three experiments.

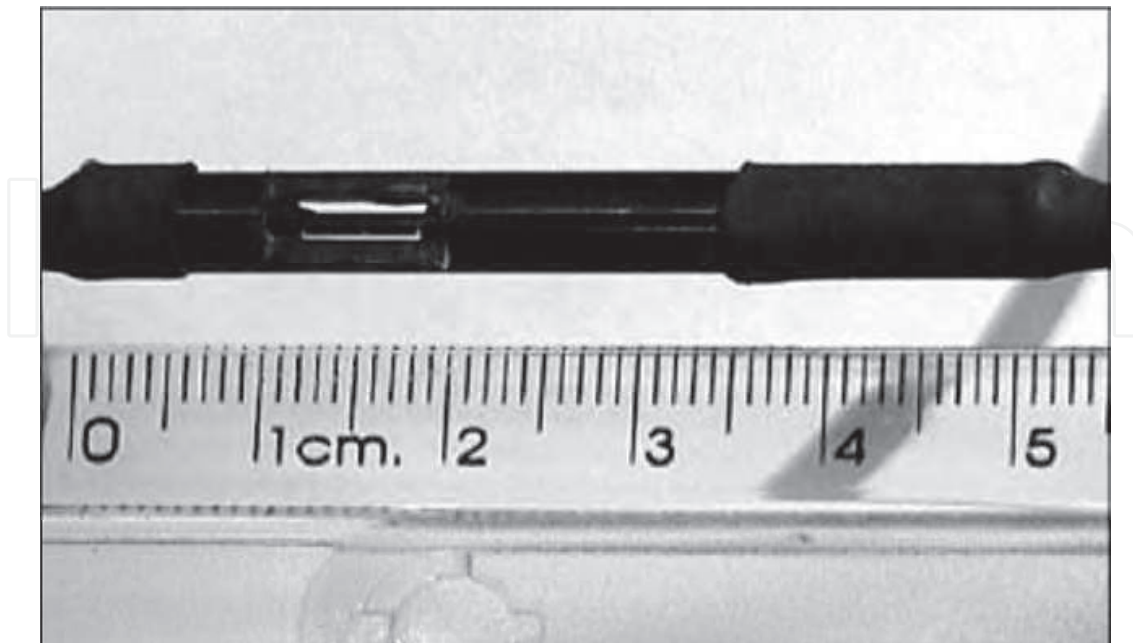Figure 7 shows the fiber optic temperature sensor constructed for the hyperthermia laboratory.

Fig. 7. Fiber optic temperature sensor constructed.

3.3 Discussion

A reasonable working range for the thermometry system is between 20°C to 35°C, as the phantom is heated about 3°C to 5°C from ambient temperature. According to the required precision, the thermometer should be accurate to within ±0.2°C at the: time of calibration. Additionally, a low thermal time constant and a low drift are required. The results obtained with the developed sensor show an appropriate performance for the selected application. The sensor was evaluated using microwaves to heat the bath in the operational interval of temperature. In this situation, we found that the sensor response still remains between the confidence band. The observed non-linearity is not an important issue, since we think to digitize the readings of multiple sensors with a personal computer. That implies the use of a calibration table to obtain the temperature values relative to the optical power detected. The reported results were obtained by means of optical instruments, but the idea is to use specifically designed circuits. For this reason, we are developing an optical source and optical detector circuits, to construct a thermometer with the presented sensor. As preliminary results, we have an optical source with an excellent stability (±0.0005 dB), thanks to the use of an optic feedback technique. That grants the required long term drift requirements of the thermometer. The optical components that we are using are the pair OPF1414-OPF2414 (Optek Inc.), which operate at a wavelength of 840 nm and possess ST ports for direct connection of the sensor. The procedure of construction of the sensor is simple and the required materials are relatively inexpensive. For example, the used fiber is a standard telecommunications grade patch-cord. The sensor could be used in other applications involving temperature measurements under strong electromagnetic fields, such as power transformers, microwave antennas, etc. The measurement range could be changed simply using oil with an appropriate refraction index. One of the drawbacks is the limited range within the sensor can make the measurements.

4. Fiber optics thermometry in microwave ablation

In this section, we present an experimental setup and results of temperature measurements during MWA using fiber optics thermometry in *ex vivo* tissue (Cepeda et al., 2011). Luxtron STB MAR'05 fiberoptic thermal probes were placed 5mm above the antenna slots longitudinally to measure real-time temperature during high hyperthermia experiment (Figure 8). The fiberoptic thermal probes are connected to a Luxtron 3300 Fluoroptic thermometer, which monitors the temperature and saves the data to a personal computer via a RS-232 serial cable.
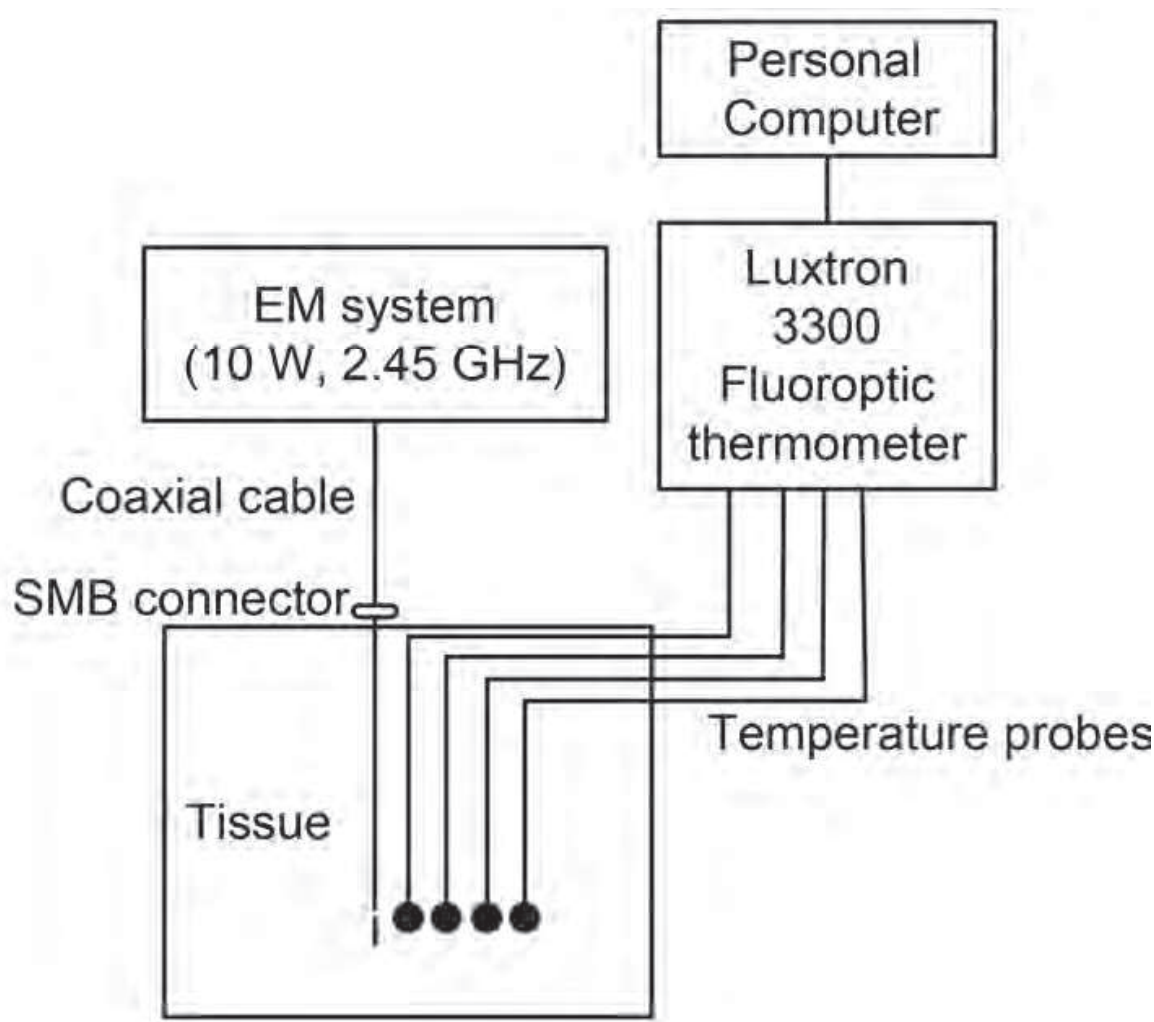
Fig. 8. Schematic of equipment and experimental setup. The antenna was completely inserted into homogeneous muscle tissue and connected to the EM system. Temperature sensors were 5 mm above the antenna slots longitudinally.

High temperature hyperthermia experiments were performed at 10 W for 3 min. The initial tissue temperature was 18 to 19 °C. Figure 9 shows the tissue with an ablated zone.

Fig. 9. A lesion created in an ex-vivo experiment at the end of a 180 s hyperthermia procedure.

The measured thermal histories at the specified locations during high hyperthermia therapy were shown in Figure 10. A fluoroptic thermometer was selected because its fiber optic temperature sensors have minimal disturbance on the antenna Specific Absorption Rate (SAR) and are unaffected by microwave radiation. Figure 11 shows a photo of *ex vivo* swine breast tissue temperature measurement, using one fiber optic during MWA.
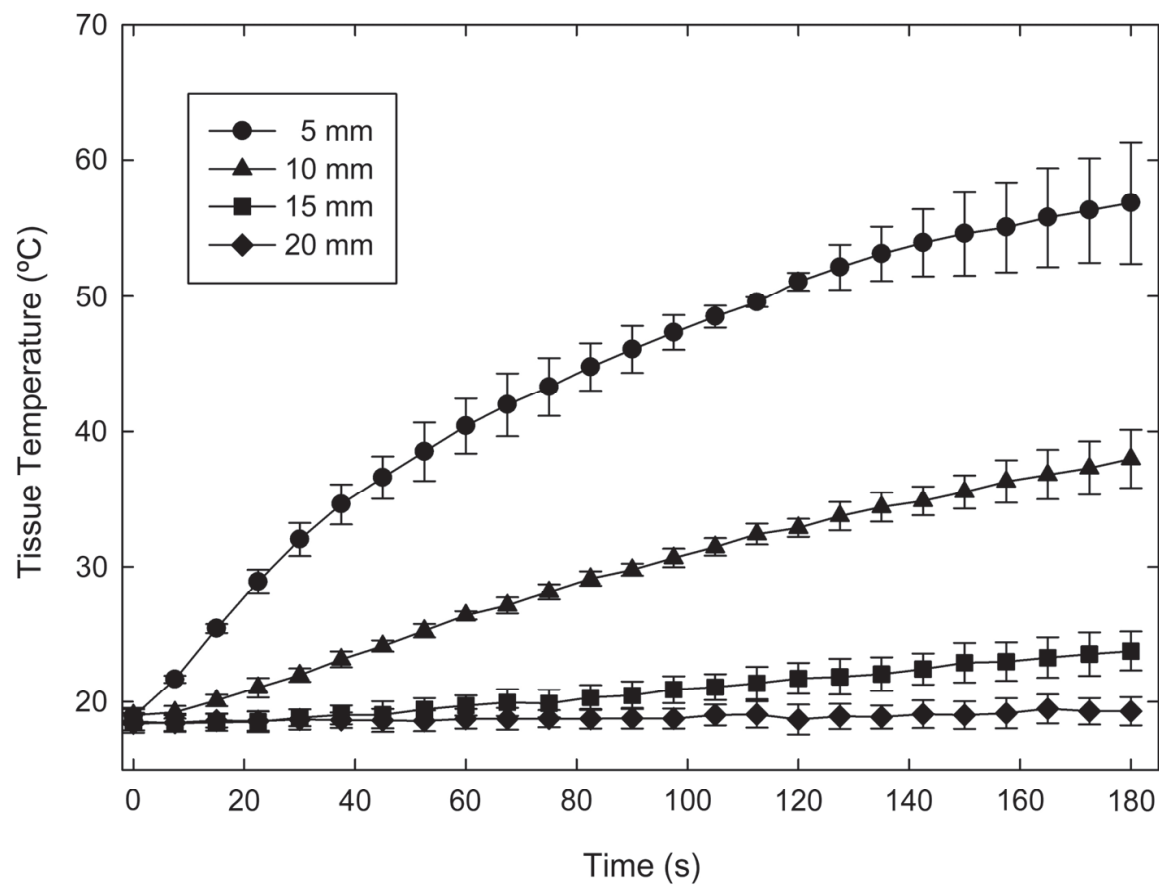
Fig. 10. A lesion created in an ex-vivo experiment at the end of a 180 s hyperthermia procedure.
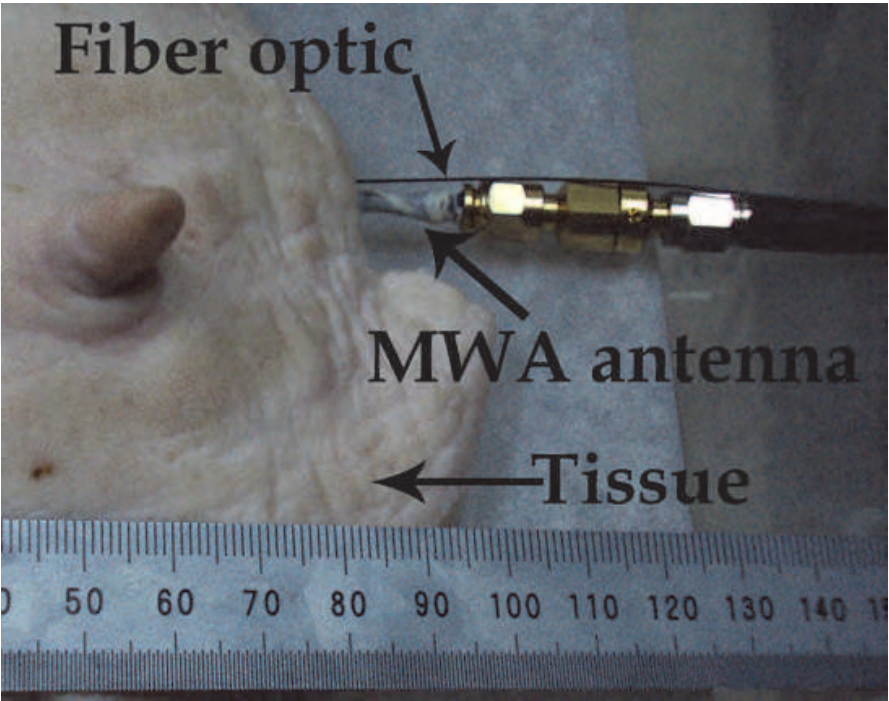

Fig. 11. Ex vivo temperature measurement in swine breast tissue.

5. Conclusion

All methods of hyperthermia involve transfer of heat into the body from an external energy source and are currently under study, including local, regional, and whole-body hyperthermia. Local hyperthermia is used to heat a small area. It involves creating very high temperatures that destroy the cells that are heated. Microwave ablation, like radiofrequency ablation, uses heating to cause tissue necrosis. RFA heats the tissue by electrical resistive heating but MWA works on a different principle. An antenna emits microwave radiation into the tissue; this results in excitation and oscillation of polar molecules and causes frictional heating. Frequently, temperature monitoring during hyperthermia cancer therapy has been achieved using interstitial thermocouples, thermistors, or fiber optic probes. The thermocouples and other conventional probes possess numerous advantages that make them attractive to be used in the characterization of temperature in hyperthermia. Among these advantages are a small size, accuracy, excellent reliability and low cost. Furthermore, this technology also possesses disadvantages, like metallic conductive components, shielding and plug wires. These metallic parts are often the reason of considerable errors in measurement of temperature when the probes are used for characterizing equipment of hyperthermia in phantoms exposed to electromagnetic radiations. These errors of measurement are caused by three phenomena, which can be presented alone or acting in combination: sensor heating due to the induced currents, disturbance of the electromagnetic field and electromagnetic interference. Thermometers based on optical fibers offer the advantage of not possessing metallic components, and therefore they do not to disturb the electromagnetic field. Fiber optic thermometers are used when electrical insulation and electromagnetic immunity are necessary. The most relevant application includes tissue-heating temperature control during radiofrequency or microwave hyperthermia cancer treatment.

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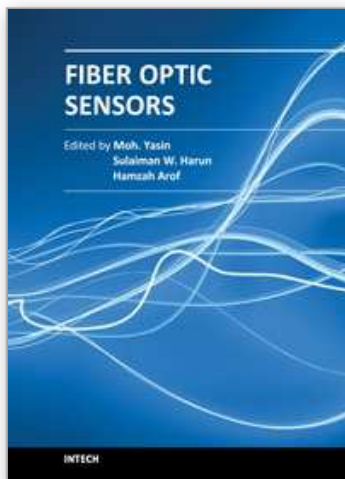
Fiber Optic Sensors

Edited by Dr Moh. Yasin

This book presents a comprehensive account of recent advances and researches in fiber optic sensor technology. It consists of 21 chapters encompassing the recent progress in the subject, basic principles of various sensor types, their applications in structural health monitoring and the measurement of various physical, chemical and biological parameters. It also highlights the development of fiber optic sensors, their applications by providing various new methods for sensing and systems, and describing recent developments in fiber Bragg grating, tapered optical fiber, polymer optical fiber, long period fiber grating, reflectometry and interefometry based sensors. Edited by three scientists with a wide knowledge of the field and the community, the book brings together leading academics and practitioners in a comprehensive and incisive treatment of the subject. This is an essential reference for researchers working and teaching in optical fiber sensor technology, and for industrial users who need to be aware of current developments and new areas in optical fiber sensor devices.

How to reference

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