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Comparative Study on Cooling System Antenna versus Non-Cooling System Antenna in Multilayer Phantoms using Low Treatment Power

Texar Javier Ramírez Guzmán
Department of Electrical Engineering/Bioelectronics CINVESTAV-IPN
México City, México.
texar.ramirezg@cinvestav.mx

Arturo Vera Hernández
Department of Electrical Engineering/Bioelectronics CINVESTAV-IPN
México City, México.
arvera@cinvestav.mx

Lorenzo Leija Salas
Department of Electrical Engineering/Bioelectronics CINVESTAV-IPN
México City, México.
lleija@cinvestav.mx

Citlalli Jessica Trujillo Romero
National Institute of Rehabilitation, Division of Research in Medical Engineering
México City, México.
cjtrujillo@inr.mx

***Abstract* — Micro-coaxial antennas have been studied as alternative treatments for different types of tumors. However, the damage to healthy tissue due to temperature rise in the antenna body is a problem that needs to be addressed to avoid the undesired heat in healthy tissue during clinical cases. To reduce the heating of the antenna body, the design of a cooling system that avoids damage to healthy tissue has been proposed. Moreover, this system allows the use of low input powers levels, i.e., lower than 20 W. Therefore, a cooling system, with circulating water (19°C) through the antenna body, was designed and built. This cooling system was tested in two micro-coaxial antennas, a monopole antenna, and a double slot antenna. The performing experiments were done in a multilayer phantom by using 10 W input power applied per 5 minutes. The results show a decrease of 6°C in healthy tissue and a power loss of 6.5% when the cooling system was used.**

***Keywords* — thermal ablation, micro-coaxial antenna, cooling system, bone tumors, heating pattern.**

I. INTRODUCTION

The procedure for a typical ablative therapy involves the introduction of a small catheter to insert the antenna into the tumor, aided by an image-guided system. Once the target is located, microwave energy is applied through the antenna tip to the target, the antenna irradiates energy that produce heat in the tissue. Temperatures higher than 60°C must be achieved to produce thermal ablation [1]. Generally, to produce a therapeutic effect, the controllable parameters for lesion size are the amount of energy delivered and the treatment time [2].

One of the challenges when using micro-coaxial antennas to generate thermal ablation in tissues is the presence of heating in the antenna body due to the flow of the microwaves through it. This effect could produce burns in the surrounding healthy tissue layers. Among the possible solutions to avoid this heating, there are three main options: 1) to reduce the work power, 2) to reduce treatment times and 3) to incorporate a cooling system. By decreasing input power or treatment time, the reached tissue temperatures tend to be lower, as well as the ablation volume. On the other hand, the incorporation of a cooling system to the micro-coaxial antennas solves the problem of the antenna heating by circulating a liquid throughout the antenna. Therefore, not only the heating is avoided but also the damage to healthy tissue such as muscle and skin. The use of cooling systems for micro-coaxial antennas has been reported in the literature. These reported cooling systems consist of a plastic tube that completely covers the antenna, with a circulating cooling medium, for example water, to produce a decrease in temperature throughout the antenna body. However, the incorporation of these conventional cooling systems results in an increase of input power, as well as treatment time to avoid the reduction of tumor damage. In 2016, Q. Fan proposed a cooling system using water as a cooling medium; it was tested in pig liver by application time of 20 minutes. In this case, the heating in the body of the antenna, and the size of tissue lesion were reduced [3]. In 2018, H. Fallahi used a conventional cooling system tested in pig liver, the water that circulated through the system was at a temperature between 30°C and 40°C, with an input power between 30 W and 50 W applied per 90 seconds [4]. On the other hand, in 2019, M. Wu conducted experiments on bone with a conventional cooling system using water as a cooling medium with an input power of 60 W applied per 6 minutes [5]. In literature, the main problem if the use of high input powers (60 W) when a conventional cooling is incorporated. These high input powers are used to prevent the reduction of the ablation zone. However, a new cooling system that does not modify the antenna performance, i.e., that allows the use of low input power (20 W), and treatment times (<10 min.) is required.

In this study, the design of a new cooling system for micro-coaxial antennas is proposed. This system helps to reduce the antenna body heating to avoid damage in healthy tissue without affecting the antenna performance. Moreover, it allows the use of 10W of input power applied for just 5 minutes.

II. METHODOLOGY

A. *Cooling system design*

A conventional cooling system completely cover the antenna body with a plastic tube through which water circulates

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to reduce the heating of the antenna. The proposed cooling system has an important modification compared to conventional cooling systems. The proposed cooling system do not completely cover the antenna body, i.e., the section of the antenna that is in contact with the tissue to be treated, in this case bone, is exposed, as shown in figure 1. This modification avoids modification of the antenna performance. In addition, low input power and treatment time are maintained.

To choose the diameter of the plastic tube, it is not only important that the antenna fits the tube, but also that there is a gap between the antenna and the plastic tube through which the water will flow. A higher flow of water in the cooling system allows a higher dissipation of the heat generated by the antenna. This helps to reduce the heating of the antenna body. However, the larger the diameter of the tube, i.e., ≥2 cm, the larger the incision needed to insert it in the tissue to be treated. On the other hand, if a smaller diameter is chosen, for example 0.5 cm, the damage to the tissue due to the tube insertion will be reduced, but the flow of water in the tube will be less. Despite this, one way to compensate the use of a small diameter plastic tube and increase the flow of water is to increase the power of the water pump. If the power is increased, the flow of water in the plastic tube will be higher, even if the tube diameter is smaller. Taking these conditions into account, the dimensions, and the design of the first version of the cooling system are shown in figure 2.

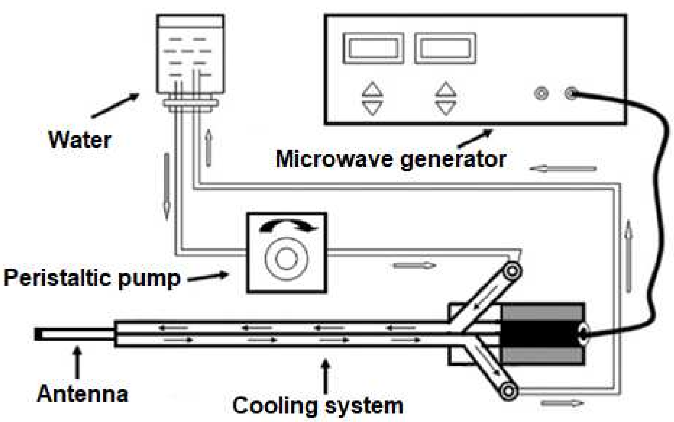

Figure 1. Diagram of the cooling system proposed for micro-coaxial antennas.

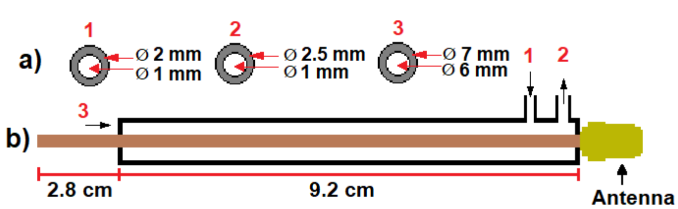

Figure 2. Dimensions of the cooling system. a) Tube diameter and b) positioning of the cooling system on the antenna.

The main tube of the cooling system (3) has an internal diameter of 6 mm; while the diameter of the antenna is 2.2 mm, this leaves a 3.8 mm gap for water to flow into the cooling system. 2.8 cm of the antenna tip are outside to the cooling system, this length was chosen because the greatest amount of electromagnetic propagation of the antenna is generated from the tip of the antenna up to 2.8 cm above it. On the other hand, the water pump chosen for this cooling system is the YX DC12v 385 pump, which generates a water flow of 3 L/min at 12 V. In this case, considering the dimensions of the cooling system tubes, the pump generates a water flow of 75 mL/min.

B. Experimental configuration

The microwave system consists of an SSPA Aethercomm power amplifier and a Rohde & Schwarz SML03 microwave generator that works at a frequency of 2.45 GHz. On the other hand, a thermometry system, based on optical fibers, Luxtron MAR05 STB, was used to record the temperatures during experimentation. These experiments were carried out with the monopole antenna (MTM) and the double slot antenna (DS) designed and optimized to treat bone tissue [6]. The input power was set at 10 W applied per 5 minutes, while the temperature of the water in the cooling system was 19°C (room temperature). A Fluke Ti32 thermal camera was used to acquire the heating pattern of the antennas. The experiments were carried out with and without the cooling system to compare the results. Figure 3 shows the implemented experimental setup.

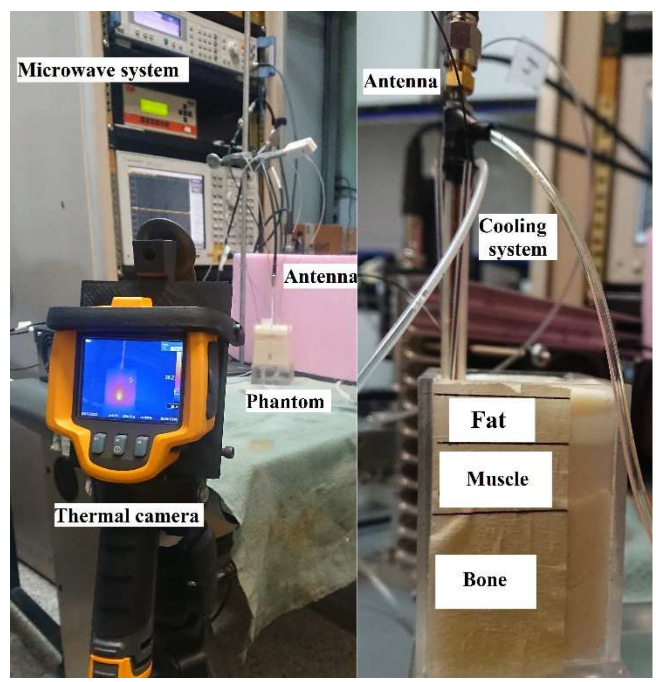

Figure 3. Experimental configuration in microwave ablations by using micro-coaxial antennas.

To evaluate the behavior of the cooling system, temperature, power loss and heating patterns were analyzed. Figure 4 shows the location of the temperature sensors used to evaluate the reached temperatures at different distances. Sensors S2 and S3 were placed at 2.8 cm from the antenna tip and at 0.5 cm and 1 cm from the cooling system, respectively. They were located at the bone-muscle interface, to evaluate if healthy tissue temperature decrease. In addition, the sensor S1 was placed at the antenna tip to assess whether the cooling system affects the heating in the zone of greatest radiation of the antenna.

C. *Biological tissue emulators (phantoms)*

The evaluation of the system was carried out on multilayer phantoms, not only to evaluate its performance, but also the possible issues that could arise during its use. These phantoms emulate the dielectric properties (electrical conductivity and relative permittivity) of biological tissues, in this case, bone, muscle and fat. Table I shows the tissue dielectric properties reported in the literature. On the other hand, Table II shows the materials used to make the phantoms.

III. RESULTS

A. *Power lost*

The power lost during the experiments is a measure that helps to understand the amount of energy that is not being delivered to the medium, in this case the phantoms. Table III shows the results of the power loss recorded at the beginning and at the end of the experiments with and without the cooling system.

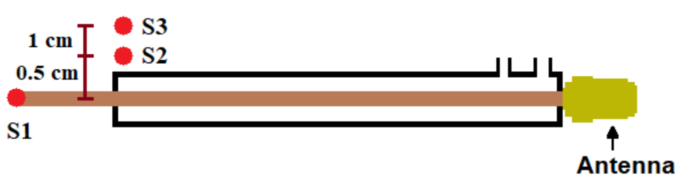

Figure 4. Location of the temperature sensors during the experimentation.

TABLE I. DIELECTRIC PROPERTIES OF THE TISSUES REPORTED IN THE LITERATURE [7].

Properties	Cortical bone	Muscle	Fat
Relative permittivity (ε_r)	11.4	52.7	10.8
Electrical conductivity (σ) (S/m)	0.394	1.74	0.26

TABLE II. MATERIALS CONCENTRATION TO THE ELABORATION OF MULTILAYER PHANTOMS [6].

Material	Cortical bone	Muscle	Fat
Distilled water	25 mL	50 mL	10 mL
Dextrose	7.2 g	---	---
Wheat flour	60 g	---	---
Corn oil	30 mL	---	30 mL
NaCl	---	0.505 g	---
Agarose	---	0.97 g	0.9 g
Ethyl alcohol	---	42 mL	---
Neutral soap	---	---	6 mL

The MTM antenna performance shows that the power loss is lower without the cooling system than with it (9.4% vs 18%). In this case the power loss reached with the cooling system was twice as high compared to the one reached when the cooling system was not included. For the DS antenna, the power loss was lower with the cooling system than without it (6.5% vs 15.8%). Moreover, it is important to address that the highest power loss was 1.58 W.

B. *Maximum temperatures*

The temperatures recorded by the temperature sensors showed the performance of the cooling system, as shown in table IV. In the MTM antenna, sensor S2, located at 0.5 cm from the antenna body, reached 42°C when the cooling system was not incorporated. However, if the system is used, it reached a maximum temperature of 37°C, this indicates that the cooling system reduced the temperature around 5°C at 0.5 cm from the antenna. For sensor S3, at 1.5 cm from the antenna, a maximum temperature of 40°C was reached, without the cooling system; while with the cooling system, the reached temperature was 30°C, i.e., a reduction of 10°C was presented. In sensor S1, the maximum temperature was 87°C without the cooling system, while with it the reached temperature was 81°C. This indicates a decrease in temperature of 6°C at the antenna tip.

On the other hand, the DS antenna shows a particular behavior. In sensor S1, a large decrease of temperature was seen when the cooling system was incorporated. At the end of the experiments, without the cooling system, the reached temperature was 102°C, while with the system, it was 84°C. These means that the cooling system helps to reduced 18°C the temperature at the antenna tip. However, for sensors S2 and S3 the opposite behavior was observed. Temperatures in S2 and S3 increased 3°C and 2°C using the cooling system, respectively. This was because in the experiments with the cooling system, the power loss was lower than the one obtained without it, this means that more power was delivered to the phantom, therefore, higher temperatures were reached.

TABLE III. LOST POWER DURING THE EXPERIMENTS USING 10 W AS INPUT POWER.

Power lost	MTM antenna	MTM antenna / cooling system	DS antenna	DS antenna / cooling system
Start	0.94 W	1.8 W	0.12 W	0.65 W
Finish	0.51 W	1.02 W	1.58 W	0.46 W
%	9.4 %	18%	15.8%	6.5%

TABLE IV. MAXIMUM TEMPERATURES REACHED IN THE EXPERIMENTS AFTER 5 MIN.

Antenna	S1	S2	S3
MTM	85.9°C	43.47°C	40.39°C
MTM cooling system	80.87°C	37.32°C	29.11°C
DS	101.81°C	42.26°C	33.59°C
DS cooling system	83.81°C	46.18°C	36.72°C

C. *Heating pattern*

The heating patterns help to visually understand how heat is spread in the phantom. These heating patterns were obtained by a thermal camera [8]. Figure 5 shows the behavior of the heating patterns with and without the cooling system. The results show that the shape of the heating pattern is affected by using the cooling system. It was observed that the use of the system reduces the heating in the upper part of the heating pattern. However, despite this reduction, the shape of the heating pattern now becomes thicker on the sides.

IV. DISCUSSION

The evaluation of this new cooling system prototype provided important information that could help to improve its performance. The goal of the cooling system is to prevent healthy tissue from being damaged by temperatures above 42°C; however, the results showed a cooling effect in the phantom, going from 37°C to 30°C, a behavior that is undesired. Our main goal is to regulate the temperature in healthy tissue (<42°C), but not to cool down it. So, a more complete evaluation of the cooling system by using different water temperatures, will help us to find the most adequate water temperature to maintain the healthy tissue temperature around 37°C.

Regarding the power loss in the experiments, the MTM antenna presented a lower power loss without the cooling system, this power loss increases twice when the cooling system was incorporated. On the other hand, the DS antenna had the opposite behavior; the power loss is less when the cooling system was implemented, and the power loss increases twice. The MTM antenna had a maximum power loss of 18% with the cooling system, while the maximum power loss of the DS antenna was 6.5%.

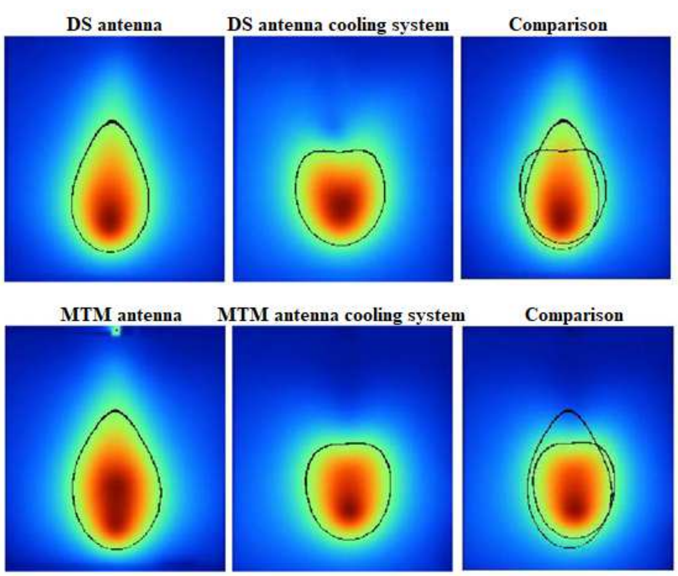

Figure 5. Heating pattern generated by micro-coaxial antennas using and without the cooling system after 5 min of radiation.

The evaluation of the heating patterns showed that the cooling system modifies the shapes of the temperature distributions. This performance was expected because the temperature of the antenna body was regulated to prevent damage to healthy tissue (muscle and fat). Although the shape of the heating patterns was modified, this modification was most evident at the top of the heating pattern, where the bone-muscle interface is found in the phantom. This indicates that the cooling system avoids heating the muscle and focuses the damage only on the bone. Even so, it is of great importance to know the amount of bone damage to quantitatively determine the area of bone that is damaged in the experiments.

Although the literature reports results in *ex vivo* porcine soft tissue, such as liver, when implementing the conventional cooling system, the input powers vary between 30 W and 60 W from 90 s to 20 minutes to reach ablation temperatures. Now, by including this new cooling system, the input power is 10 W for 5 minutes in bone tissue, exceeding ablation temperatures.

V. CONCLUSION

In the MTM antenna the cooling system reduced the muscle temperature by 6°C, keeping it in a range of 37°C; while in the DS antenna, the temperature in the muscle layer increase 4°C. Furthermore, the maximum power loss was 18% in the MTM antenna and 6.5% in the DS, both with the cooling system. In addition, the incorporation of the cooling system in the DS antenna improved the coupling with the tissue compared to not using this cooling system. On the other hand, the heating patterns show that the cooling system modifies the patterns but improves bone targeting by reducing damage to the muscle layer. Even so, it is necessary to calculate the amount of necrotic tissue to determine whether the cooling system reduces the area of tissue damage. Finally, this proposed cooling system allows ablation temperatures to be generated by lowering the temperature in healthy tissue using an input power of 10 W for 5 minutes.

As future work, it is necessary to calculate the ablation areas to determine tissue damage, as well as the analysis of the cooling system performance by using different water temperatures to have a complete evaluation of the cooling system.

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