Thermometry studies of radio-frequency induced hyperthermia on hydrogel based neck phantoms

ABSTRACT
A cylindrical phantom, resembling average human neck, was prepared by using hydrogel sheets containing vinyl and polysaccharide. The phantom was used to obtain temperature distributions for 6 values of input power of radio frequency (RF) at 8MHz, by invasive thermometry technique, using thermistor probes.

The inclusion of cervical vertebrae and calcium carbonate pieces (human bone representative) with a hollow tube (windpipe equivalent) in the phantom simulates the change in thermal distributions. This is similar to the alterations in heat disposition obtained in the real human neck, during RF induced heating, without extensive distortion of the uniform temperature distribution provided by the RF heating instrument.

This paper compares the hydrogel neck phantom with other phantoms, that have been developed for studying thermal distributions and optimization of novel non-invasive thermometry techniques in hyperthermic oncology.

Key words: Radio frequency, Hydrogel, Phantom, Thermometry

INTRODUCTION
Since the success of hyperthermic oncology, models resembling real human body parts, known as phantoms, have been an important requirement, to provide leads for development of innovative techniques in effective thermal treatment in malignant tissues.

Generally, the phantoms are designed mainly for simulating specific electrical and/or thermal properties of a complex organ, in order to understand the disposition of heat in the region of interest. Hence mapping the temperature distribution in healthy and malignant tissues is of great importance.

The objective of the research is to develop cost effective and simple phantoms, compliant with industrial and medical standards. This is to simulate the heat distributions of the region of interest and obtain a clear picture of the temperature distribution, provided by a particular input (forward) power of RF heating.

The hydrogel sheet, used to prepare the phantom contains vinyl and polysaccharide, are similar to human body tissue with respect to its density, thermal conductivity, and di-electric constants. The hydrogel phantom proves to be more advantageous, as it closely simulates the thermal distribution, of the average human neck and provides the actual temperature distribution given by the hyperthermia-heating source.

The method of invasive thermometry is utilized in this experiment, involving one reference temperature thermistor probe at the center of the phantom, and the experimental thermistor probe to measure temperature at different points in the phantom. The invasive thermometry technique is simple and provides a 3-dimensional temperature distribution, in the phantom.

With developments in hyperthermic oncology, there has been a simultaneous development for non-invasive thermometry of tumors, using magnetic resonance (MR) thermography and proton resonance tomography that records phase changes in accordance with temperature distribution.

It is well understood that the anatomy of different areas in human body, posses different thermal and electrical properties with respect to tissues densities, inorganic content and tissue fluid flow rates, causing alteration of the original temp-
perature distributions provided by the heating source for hyperthermia.

In the past, mathematical simulation using geometric modeling, has been developed by Lagendijk et al. to accurately study and analyze thermal distributions and heat transfer between tissues and blood vessels.

The real temperature distribution is dependent on both, the input power of the non-ionizing radiation, provided by the RF heating instrument and the heat transfer dynamics in the specified tissue region.

Mathematical models for studying heat transfer in different tissues of the human body, has proven to be an important tool for optimizing the delivery of optimum thermal dose to malignant tissues, with minimal damage to surrounding healthy tissue.

In order to optimize the appropriate thermal dosage to the target, it becomes necessary to understand temperature distributions and thermal [specific absorption rates(SAR)] patterns, produced in the malignant region and provided by the heating source.

The Phantoms developed in the past; either included tissue equivalents of bone/muscle/fat or contained actual tissue components from human or animal source. Such phantoms, closely simulated the actual body part for which thermal distribution was to be studied, and thus provided a clear picture of the heat disposition in the organ.

Scientists, Lagendijk and Nilsson,[9] developed a simple procedure for producing cost effective and easy to handle phantoms, which contained bone, fat and muscle equivalents. They combined their phantom with high water content phantom to obtain the RF power absorption pattern similar to structured tissues. Similarly J Crezee et al,[10] used a muscle equivalent phantom to study invasive thermometry in Radio-Frequency (at 27 MHz) hyperthermia.

But the major disadvantage, was the inability of the phantom to exhibit the temperature distribution provided by the hyperthermia-heating instrument.

The other type of previously developed phantom, constituted of materials that possessed specific heat capacity, thermal conductivity, di-electric constants, similar to body tissue. The commonly used materials were gel[8] and agar-agar[11] with saline, for dosimetry studies in ionizing and non-ionizing radiation.

The phantoms provided accurate thermal distribution patterns, induced by the hyperthermia heating instrument, and the results were reproducible in such types of phantoms, because the key constituents were available from standard commercial sources.

The muscle equivalent phantoms[6] are made out of a molten mass consisting of agar, sodium chloride, preservatives and deionised water, which is then allowed to solidify in a vessel of desired shape and size. While bone phantoms, are made by suspending a bond part of region of interest like cervical vertebrae of neck region, in the molten mass, followed by solidification.

Based on similar constituents, Scientists, Frank. Seifert and Werner Hoffmann[12] at the NMR Measuring techniques work group at Physikalisch-Technische Bundesanstalt, developed a drum-size phantom for deep body hyperthermia using RF. The phantom used here is an elliptical plastic tube containing multiple agarose layers, with temperature-sensitive contrast agents, surrounded by a water bolus. The whole phantom, is again covered with a outer shell for inserting microwave or RF radiation antennas.

But such phantoms, fail to provide the accurate thermal distributions, which would be produced in real body parts.

In addition to obtaining thermal distribution patterns, in hyperthermic oncology, both types of phantoms, have significantly contributed in optimizing new treatment techniques and development of non-invasive thermometry methods.

Pethig’s research work involved[7] the developing a technique tissue imaging based on their di-electric properties, known as electrical impedance tomography. The technique also utilizes the hyperthermia microwave or RF radiation, for imaging. Keeping in mind, the different di-electric properties of normal, malignant and benign tumours, the optimization of the imaging method by developing phantoms which closely resemble malignant and normal tissues.

A similar innovative report from Rama Jayasundar,[8] demonstrated the utilization of radio frequency for both tumor heating and monitoring the thermal distribution by temperature dependent studies of MR thermography.

The study was conducted on agar phantoms with varying concentrations of NaCl.

It is necessary for a phantom, to strike a balance by simulating the thermal distribution patterns provided by the heating instrument and exhibit the accurate temperature distribution in the region of interest, during hyperthermia.

Recent innovative developments in phantoms, have made them capable of achieving the balance successfully, where Meaney and Coworkers, studied comparisons in finite ele-
ment computations, of the deep heating characteristics of the sigma 60 applicator, using a relatively complex phantom to represent the pelvic regions, known as the Utah phantom. The phantom simulated the pelvic region effectively, and also exhibited the sharp increases in electric field, when it was polarized perpendicular at the fat/muscle interface.

The details of the preparation and investigation of the invasive thermometry of the hydrogel neck phantom is given as follows.

**METHODS AND MATERIALS**

10 sheets of Hydrogel of Hi-Zel™, from ABS Medicare (SIZE: 5mm thickness, 150 mm width and 200mm length), were used. Each sheets consists of Poly Vinyl Alchohol (8.333 gram), Agar Agar (0.521 gram), Carrageenan (1.042 gram) and Purified Water.

Most of the sheets were stacked one above the other and the remaining were used to cover the sides, to make a neck shaped cylindrical phantom.

The dimensions of the phantom: 150mm (length), 100mm (diameter) and 100mm (width).

The radio-frequency induced heating is provided by Thermotron RF-8 (Vinita Yamamoto Inc., Japan), operated at frequency of 8 MHz.

From the center of the circular face of the phantom, the reference probe is inserted 7.5 cm inside. The experimental probe, is placed 7.5 cm inside the phantom, in order to record temperatures at every 10mm away from the reference probe, along X axis (+ve/-ve) and at every 5mm away from the center along Y axis (+ve/-ve).

Both temperature probes can measure a minimum temperature of 0.1°C.

Before RF heating, precooling of the phantom was conducted on its lateral sides, by two water circulating pads (temperature controlled at 5°C), which cover the electrodes.

The pre-cooling is carried out for patients having pelvis and stomach cancer, as these regions contain sufficient layer of fat. Hence in order to improve heat penetration and to avoid thermal/electrical burns, due to absorption of electrical fields and heat by the fat layer.

[Figure 1.C] Pieces of chalk (Caco3) and cervical bones to represent bone, are placed inside the phantom, 10mm below the reference probe. The chalk pieces, are similar to bone in its basic mineral content, but not in its physical structure, thus partially resembling the di-electric and thermal properties of bone.

A [Figure 1.B] hollow plastic tube, representing windpipe, is placed 1 cm, above reference probe. Temperature distribution in the bone-representing region, is separately conducted for calcium carbonate pieces and cervical bones.

The pair of electrodes of 10 cm f diameter, were used, where one electrode is kept active (emits RF radiation), while the other is passive, for receiving the radiation. The hyperthermia machine, is thermostatically controlled so as not to exceed heating beyond 49°C. The temperature of both the water circulating pads is kept 5°C, hence the heating of the phantom is more in the center, than the surface.

The low temperature of the pads, provides cooling below the phantom surface, allowing the heat to penetrate towards center. The electrodes are positioned on lateral sides (right and left) of the phantom, parallel to each other. (f symbol represents circular shape)

Initial preliminary thermometry studies were carried out at 300W, 400W, 600W, 700W and 800W (W = Watts) values of input power [or forward power (F)]

While, detailed thermometry studies were conducted at input power of 500W for circulating temperatures of 20°C and 5°C.

During initiation and continuation of the RF induced heating, the temperature measured in the phantom at any particular point, is not constant. Hence the extent of heating would be expressed in % with respect to temperature of the reference probe. T1 = Reference, T2 = Experimental, and extent of heating is (T2/T1) x 100 expressed in %

![Image of the Hydrogel Phantom with annotations:](image_url)

**Figure 1:** Photograph of the Hydrogel Phantom

A) Hydrogel sheets B) Plastic hollow tube representing the wind pipe. C) Calcium carbonate pieces, representing bone.
The power losses, [or reflected power (R)] when the electrodes are not parallel to each other, is to be kept at a lowest possible value, in order to provide efficient heating, by allowing maximum amount of RF radiation from the active electrode to the passive electrode.

**RESULTS**

The preliminary studies, were carried out for 5 values of forward power (F) of 300 W, 400 W, 600 W, 700 W and 800 W (W = Watts).

For forward power of 300W and 400W, high temperature spots (extent of heating $\geq 100\%$) of around 50°C to 51°C, was observed at 10 mm away from the center, towards top and right side. But as the forward power was increased from 400W onwards to 700 W, the high temperature spots were observed at 5mm away from the center, towards the top side and 10 mm, away from center towards both right and left side. At 400 W, 700 W and 800 W, high temperature spots, are observed at 20 mm away from center, on both right and left side.

Comparatively, for 700W forward power, high temperature spots were observed at every 10 mm going up to 50mm, away from center.

For forward power values from 300W to 700W, the extent of heating ranges from 60% to 85%, from the center towards surface, in the right and left side of the phantom.
The detailed thermometry studies, for forward power 500W (conditions in Figure 1) involved temperature measurements up to 10 cm inside the phantom, in the regions of windpipe and the bone equivalent (chalk), starting from the front face of the phantom.

The extent of heat absorption is different as compared to other regions of hydrogel in the phantom, as the bone equivalent absorbs more heat (70% to 95%) as compared to the wind pipe (61% to 88%) which itself absorbs lesser heat as compared to the other hydrogel areas [Table 1]. The thermometry was conducted again, after incorporation of human cervical vertebrae, and the extent of heat absorption is much higher (84% to 116%) than the bone equivalent region.

For forward power 500 W/Reflected power of 120W, with circulation temperature of 5°C, certain high temperature spots (extent of heating ≥ 100%) of around 50°C to 51°C is observed at 10 mm away from the center on top/bottom/right/left side of the center [Figure 2]. This demonstrates that the heating is towards the center, which is due to circulating temperature of 5°C. But at 50 mm away from the center to the right, a 100% extent of heating is observed. While the extent of heating is in between 65% to 95% on distance more than 10mm away from the center.

When thermometry of Figure 2 compared with [Table 2] (F) 500W/(R) 40 W and 20°C circulation temperature. Higher extent of heating is observed more towards the surface of the phantom. The extent of heating is very high (105% to 116%) for every 10mm distance away from the center towards bottom/right and left sides. Such a uniform heating extent, is not observed in Figure 3, which is due to the higher reflected power (120 W), in comparison with Figure 3 (40 W).

The isothermal chart provided by Vinita Yamamoto Inc.of Power (F) 500 W, Power (R) 40 W and circulation temperature of 20°C [Figure 3]. The thermograph shows an higher extent of heating, towards bottom, right and left regions of the phantom, and the higher temperatures are more towards the surface than the center. This demonstrates that the thermal distribution in the phantom, is in accord with the standard isothermal thermograph charts.

**DISCUSSION**

The preliminary thermometry studies with the different values of forward power, shows a gradual decrease in temperature, from the center to the surface, due to lower temperature of circulation. In addition, the extent of heating is much higher in top, right and left sides of the phantom, as compared to the lower region of the phantom.

The alteration in thermal distribution is due to the difference in the dielectric constants and thermal properties of the windpipe and bone region, as compared to the hydrogel. This demonstrates the thermometry studies are in accord with the simulation based studies by Van Rhoon and co-workers, which was based on the distortion in thermal and SAR distribution, in neck phantoms.

The location and the distribution of the high temperature regions (96% to 100% and above), is based on the parameters such as electrode diameter, temperature of the circulation pads (covering the electrodes) and the applied forward and reflected power, respectively.

The differences in the extent of heating for the same value of forward power of 500W, is due to the difference in the values of reflected power. Figure 2, the reflected power is 3 times higher than in Figure 3. The extent of heating in Figure 3, is much higher (105% to 110%) in the center, than in Figure 2 (99% to 102%).

This shows that higher values of reflected power decrease heating efficiency, such that for the same values of forward power of 500W, the extent of heating is higher in the center, for 20°C circulating temperature, in comparison with the circulation temperature of 5°C, where heating is supposed to be more in the center.

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Table 2: (F) 500 Watts,(R) 40W, V: 2.9 kilovolts, 200C circulation temperature

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