Computational study of simplified numerical phantoms inside capacitive hyperthermia devices

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Introduction

Capacitive hyperthermia is often used in conjunction with radiotherapy and chemotherapy for the treatment of cancer. It is applied by the use of electrodes, which can be either changeable or fixed. The main frequencies used for this electromagnetic heating modality are 8 and 13.56 MHz. In order to achieve better coupling of the electromagnetic energy to the body and, at the same time, cool the surface tissues, all devices use a water bolus between the application electrode and the body, commonly with a cooled circulating liquid. However, not much work has been performed until now on the treatment planning with such devices [1, 2].

Objectives

The objective of the current study was to investigate the distributions of the electric field, the specific absorption rate (SAR) and the temperature inside a simplified numerical phantom of the human torso with an embedded spherical tumor, when the number, shape and positioning of electrodes were changed to achieve an optimized treatment. Finally, we also aimed at examining the effect of optimal positioning derived with the simplified model on a numerical phantom of realistic anatomy.

Material/Methods

The software platform we used for performing the numerical simulations was Sim4Life Version 4.4.2 (Zurich Med Tech, Zurich, Switzerland), which implements the Finite Element Method (FEM). A homogenous numerical phantom of the torso (cylindrical with elliptical cross-section) was created. The phantom comprised two tissues: an internal cylinder with small and large diameters of 40 cm and 72 cm, respectively, which was assigned to the electric conductivity of muscle, and a cylindrical shell of 2 cm thickness on top, which was assigned to the properties of fat. The realistic model of 'Ella' from the Virtual Population (IT'IS Foundation, Zurich, Switzerland) was also used and studied; this model represents a 26-year-old female with the height of 1.63 m and 57 kg. The circular electrodes simulated were of 25 cm in diameter.

Results

It was confirmed that the number and size of the electrodes induce differences in electric field (SAR) distribution. At first, we used two electrodes with different dimensions (circular and rectangular). A different geometry was applied with two electrodes with different dimensions (circular and square) with which we achieved the maximum local SAR per 100W of absorbed power in the tumor region and lower total deposited power in healthy muscle and fat tissue. Using the most efficient model we performed the thermal simulation. Through the thermal simulations we confirmed that temperature distribution changes in proportion with the applied power and boundary settings. After studying the homogenous models, we confirmed the results with the realistic model of 'Ella'.

Conclusion

We have shown that starting with a simplified numerical model of the torso, it is possible to achieve an electrode configuration, which can be used with realistic patient models to improve power deposition inside the tumor while sparing healthy tissues.

References

(1) V. D'Ambrosio, F. Dughiero. Numerical model for RF capacitive regional deep hyperthermia in pelvic tumors. Medical & Biological Engineering & Computing 45:459, 2007

(2) H. P. Kok, A. N. T. J. Kotte, J. Crezee. Planning, optimisation and evaluation of hyperthermia treatments. International Journal of Hyperthermia 33(6):593-607, 2017

ARISTOTLE UNIVERSITY OF THESSALONIKI
PHYSICS DEPARTMENT

COMPUTATIONAL STUDY OF SIMPLIFIED NUMERICAL PHANTOMS INSIDE CAPACITIVE HYPERTHERMIA DEVICES

Georgios Alexiou, Theodoros Samaras

Thessaloniki 2019

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Hyperthermia

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- Hyperthermia is a condition in which the heat generated in the body cannot be dissipated by the natural thermoregulatory mechanisms. It can be induced both naturally and artificially.
- We increase the temperature in tissues from 41 to 44 °C for 30-60 minutes. It is applied once a week for several weeks. The heat is often induced by alternating electromagnetic fields.
- Hyperthermia is used in combination with chemotherapy or radiation therapy.

Biological background of hyperthermia

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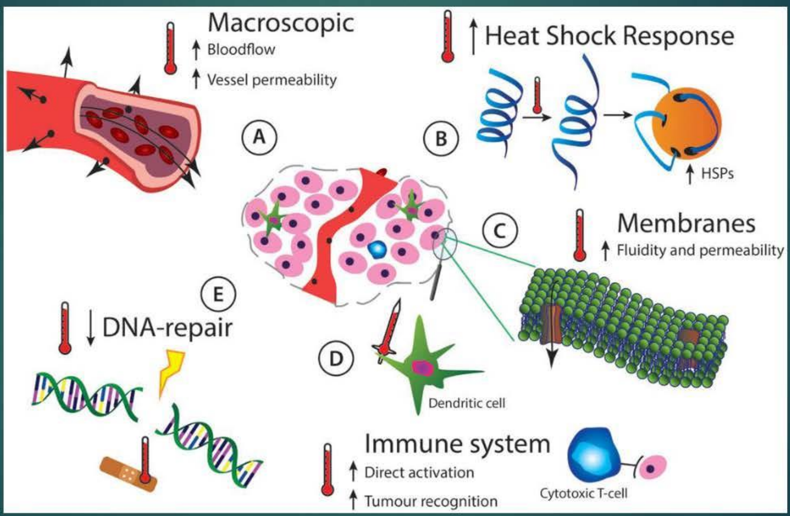

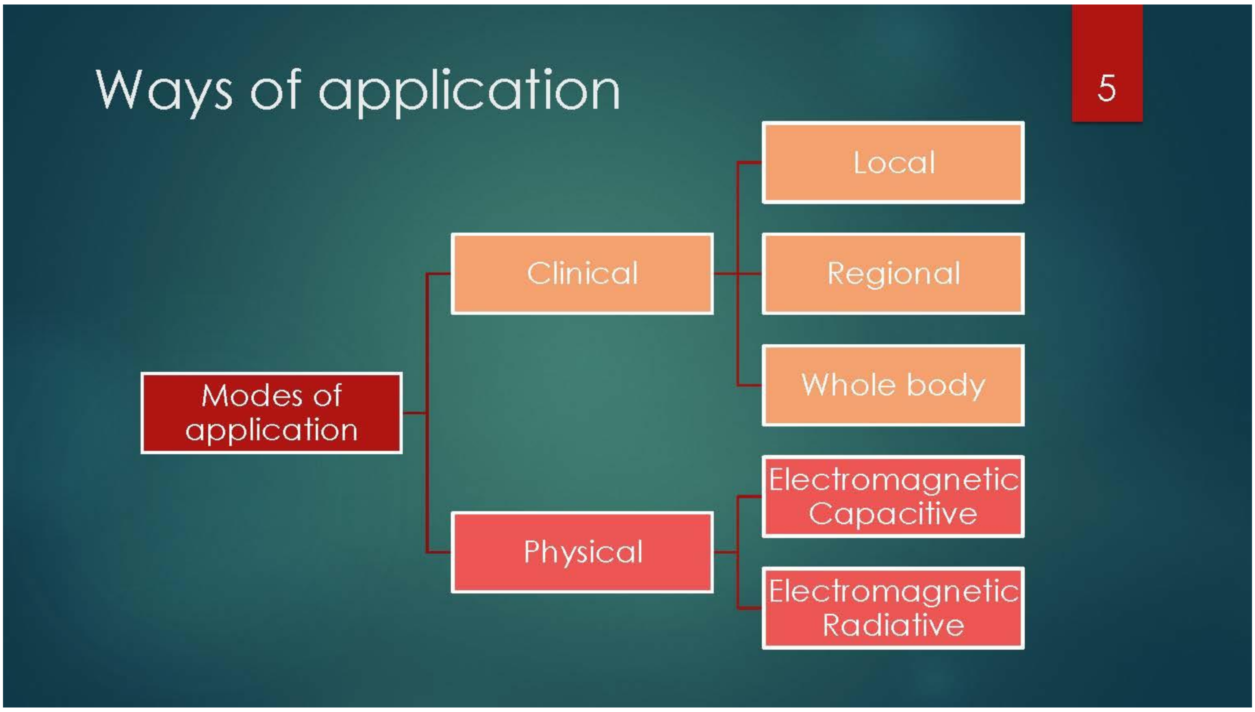
Ways of application
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Modes of application
Clinical
Physical
Local
Regional
Whole body
Electromagnetic Capacitive
Electromagnetic Radiative


Ways of application
6
The device EHY-2030 which is used in local capacitive hyperthermia (http://www.hot-oncotherm.com/about/)

Ways of application

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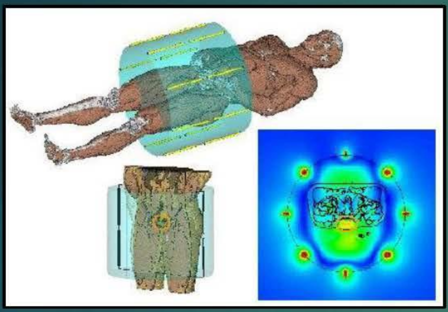

The application of regional hyperthermia (electromagnetic radiative) with the assist of ring dipole array.

The device WBH2000 for the application of whole body hyperthermia (infrared).

Treatment planning

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- **The main purpose**: To locate the exact place of **hot spots** and **cold spots**.

  This is crucial as the power is limited in great values because it causes pain in the patient.

  - Treatment planning involves the solution of systems of differential equations of some derivatives with numerical techniques because the propagation of electromagnetic radiation in human tissues is a complex phenomenon.
  - The propagation of electromagnetic radiation in human tissues is can be solved by solving Maxwell's equations numerically.

- **Result**: Finding the distribution of the electric field in tissues from which we calculate the distribution of Specific Absorption Rate (SAR).

  SAR is the deposited electromagnetic power per unit mass of tissue [W / Kg].

Treatment Planning

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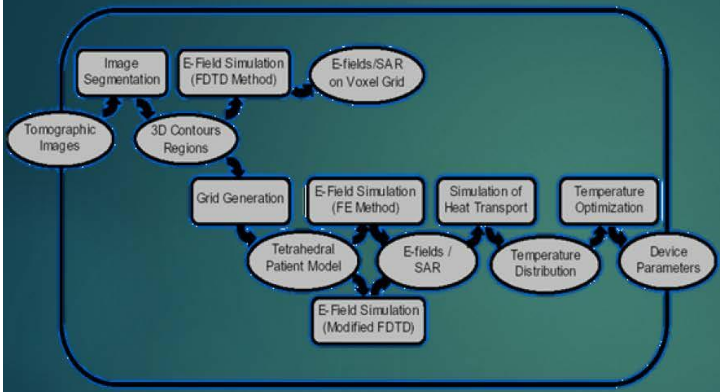

Maxwell's equations (radiative hyperthermia)

$$\bar{\nabla}\times\bar{E} = -\frac{\partial \bar{B}}{\partial t} - \bar{J}_m = -\mu_o\mu_r\frac{\partial \bar{H}}{\partial t} - \bar{J}_m$$

$$\bar{\nabla}\times\bar{H} = \bar{J} + \varepsilon_o\varepsilon_r\frac{\partial \bar{E}}{\partial t}$$

$$\bar{\nabla}\cdot\bar{H} = \frac{\rho_m}{\mu_o\mu_r}$$

$$\bar{\nabla}\cdot\bar{E} = \frac{\rho}{\varepsilon_o\varepsilon_r}$$

Bioheat Transfer Equation (BHTE)

$$\rho c\frac{\partial T}{\partial t} = k\nabla^2(T) - W_b\, c_b\,(T - T_b) + \sigma E^2 + Q_m$$

Laplace's equation (capacitive hyperthermia)

$$\nabla[\sigma(\nabla V)] = 0$$

Computational Study

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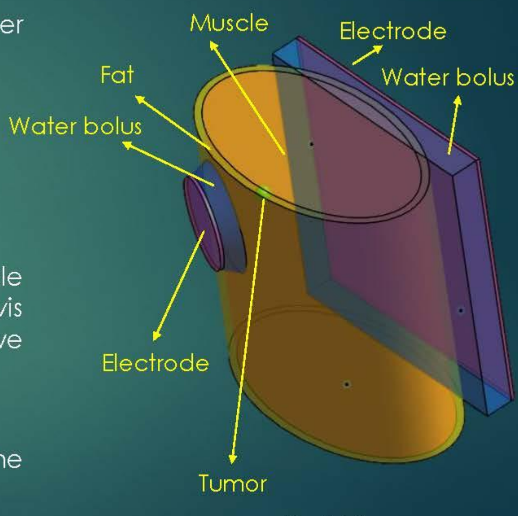
- A specific simulation platform was used in order to solve the problem:
  Sim4Life
- We used the Finite Element Method (FEM)
- We created a homogenous model with muscle characteristics (from the chest area to the pelvis area) which externally consists of fat. Also we placed a tumor inside.
- In addition we installed two electrodes with the corresponding water boluses.



Model 1

Computational Study

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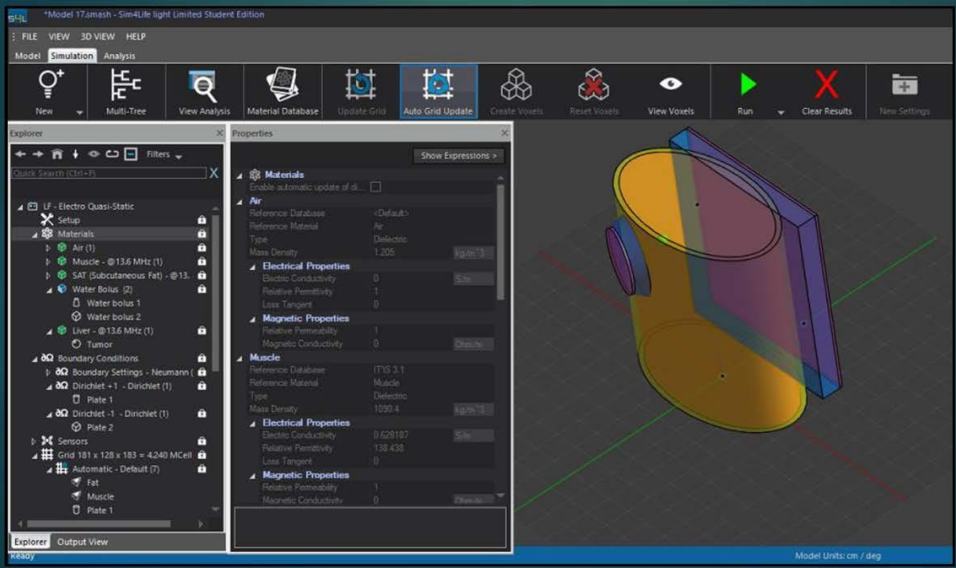

Sim4Life light 4.4.2.3851

Computational Study – Electrical Analysis

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- **Table 1.** Dielectric properties of the different parts of the model.

Body part	Density ρ (kg/ m^3)	Electric Conductivity σ_e (S/m)	Relative permittivity ε'
Muscle	1090.4	0.63	138.4
Fat	911	0.05	25.4
Tumor	1078.8	0.34	181.2
Water Bolus	1000	2	76.5

Hasgall PA, Di Gennaro F, Baumgartner C, Neufeld E, Lloyd B, Gosselin MC, Payne D, Klingenböck A, Kuster N, "IT'IS Database for thermal and electromagnetic parameters of biological tissues," Version 4.0, May 15, 2018, DOI: 10.13099/VIP21000-04-0. itis.swiss/database

1st Model

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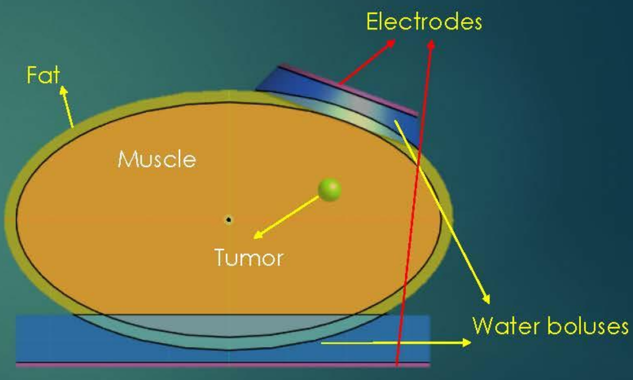
- **Voltage regulation:**
  Small circular electrode: **100 Volts**
  Large rectangular electrode: **0 Volts**
- Diameter of the small electrode: **25 cm**
- Tumor has the dielectric properties of liver and a radius of **2 cm**.



Top view of the 1st model.

1st Model

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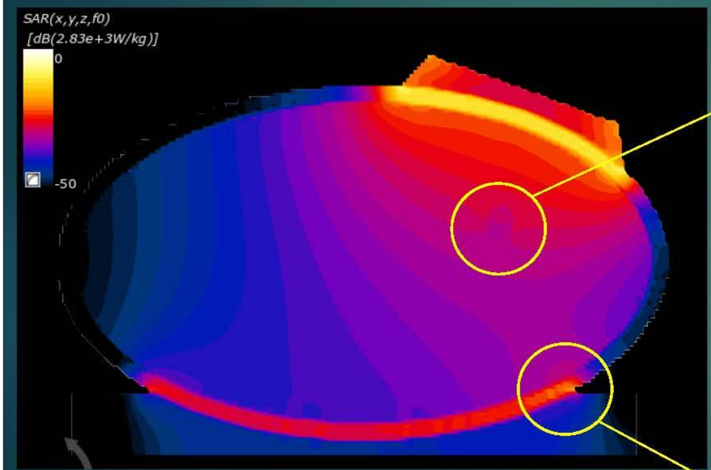
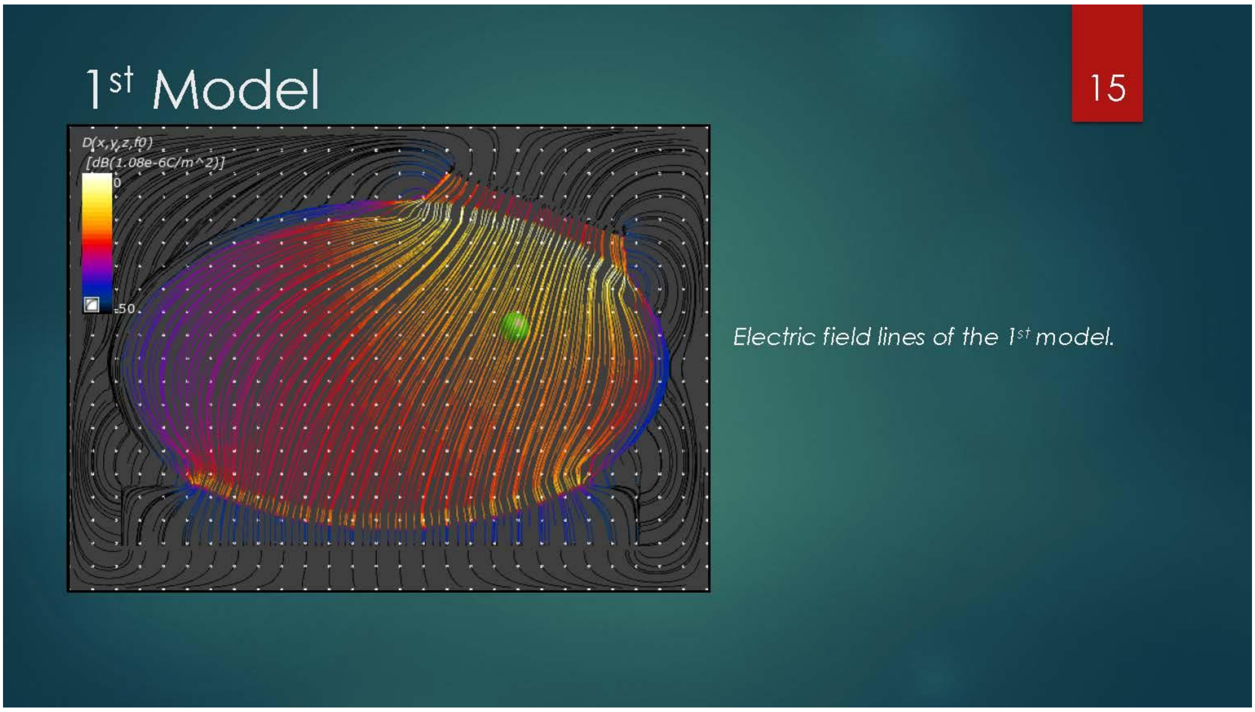
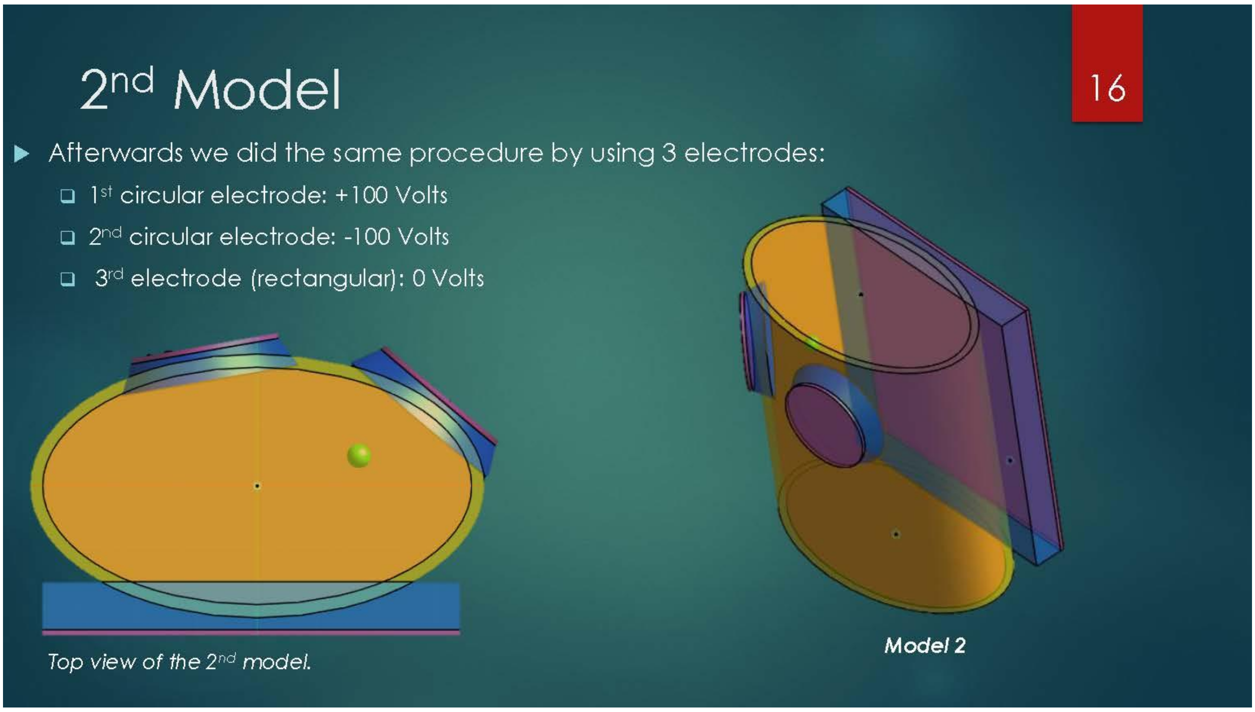


SAR distribution in the first model (top view).


1st Model
15
D(x,y,z,f0)
[dB(1.08e-6C/m^2)]
0
-50
Electric field lines of the 1st model.


2nd Model
16
Afterwards we did the same procedure by using 3 electrodes:
1st circular electrode: +100 Volts
2nd circular electrode: -100 Volts
3rd electrode (rectangular): 0 Volts
Top view of the 2nd model.
Model 2

2nd Model

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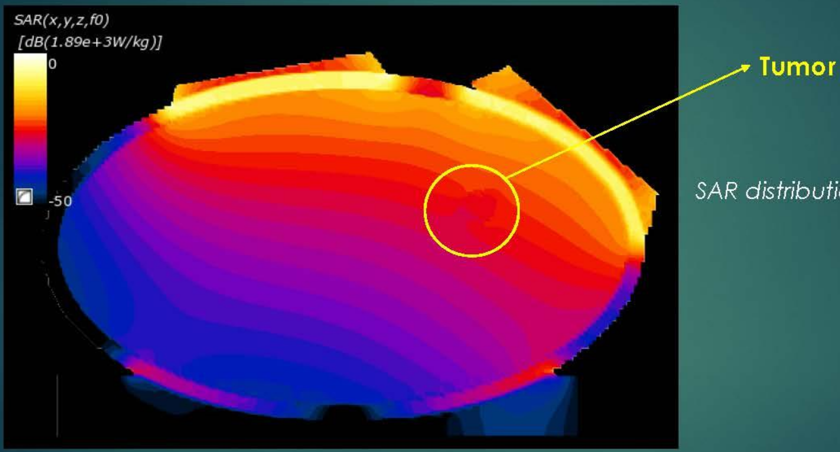

SAR distribution in the 2nd model.

2nd Model

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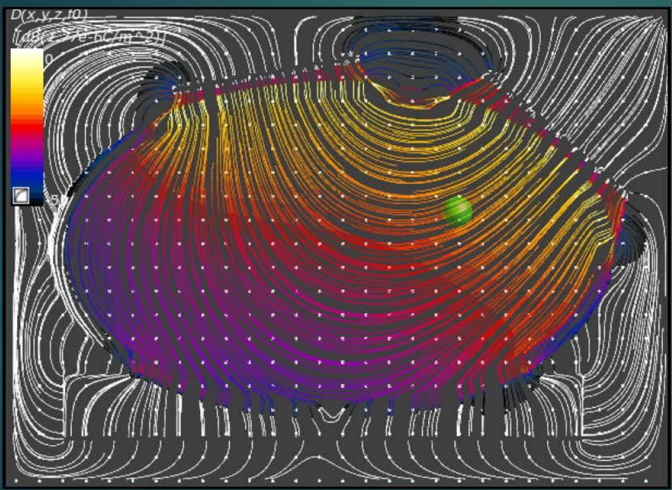

Electric field lines in the 2nd model.

3rd Model

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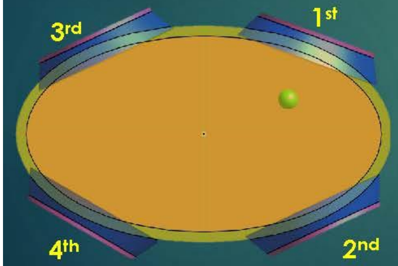
- Subsequently we replaced the large ground electrode with two small circular electrodes with the same dimensions (d = 25 cm).
  - 1st electrode: +100 Volts
  - 2nd electrode: +100 Volts
  - 3rd electrode: 0 Volts
  - 4th electrode: 0 Volts



Top view of the 3rd model.

Model 3

3rd Model

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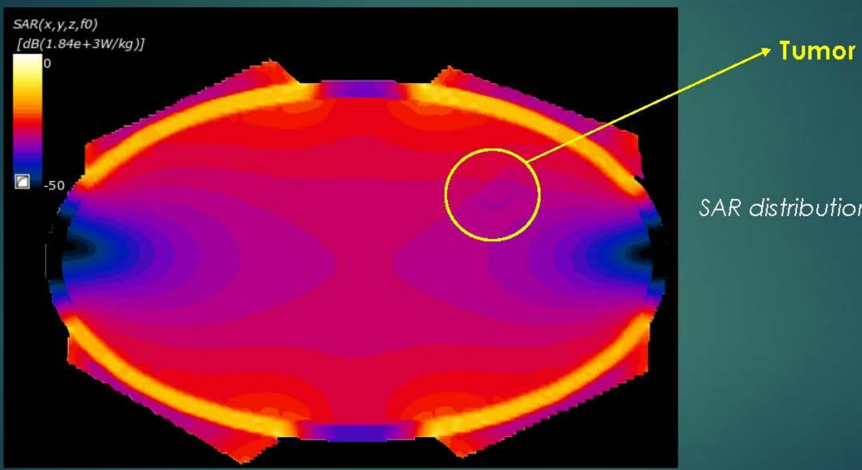

SAR distribution in the 3rd model.

3rd Model

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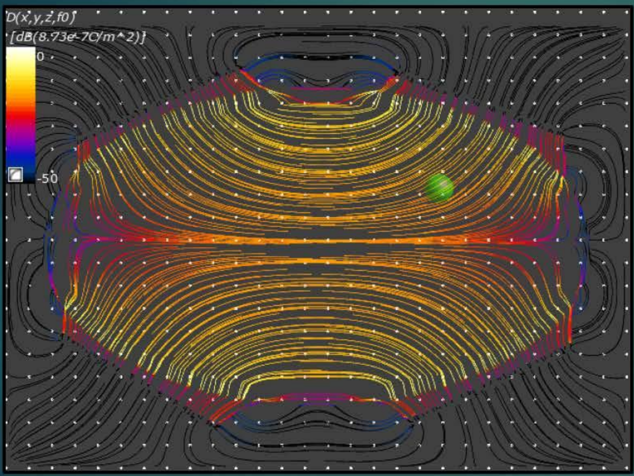

Electric field lines in the 3rd model.

Computational Study – Electrical Analysis

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- The quantity we intended to compare in the three models is the maximum local SAR in the tumor per 100 Watts of total absorbed power.

SAR^{max} (local) x100 [(W/Kg)/100Wabs]

- **Table 2.** The results of the three previous models

Model	Number of electrodes	SAR^{max} (local) in tumor [W/kg]	SAR^{max} (local)x100 [(W/kg)/100Wabs]
1st	2	3.71	0.69
2nd	3	6.33	0.52
3rd	4	2.04	0.37

Could we improve these results ?

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- While it may seem easy at first, raising the temperature inside the body by external means is quite a difficult task. Hot spots greatly limit the deposited power to tumors deep in the body.
- To improve the effect of hyperthermia we can reduce the size of the electrode (and water bolus) on the back of the patient, thereby forcing the field to pass through the tumor as much as possible.
- In the last model we used 2 electrodes. One is the same circular as before and the other is square with a side of 35 cm.

The Final Model

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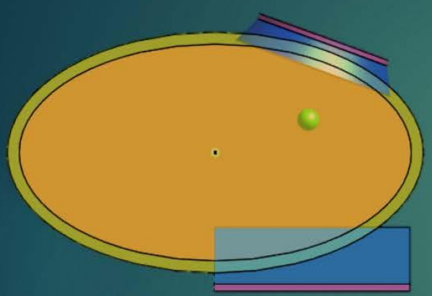
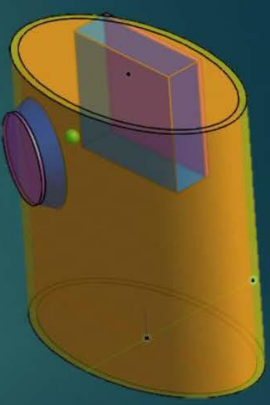


Top view of the 4th model.

- Circular electrode: +100 Volts
- Square electrode: 0 Volts



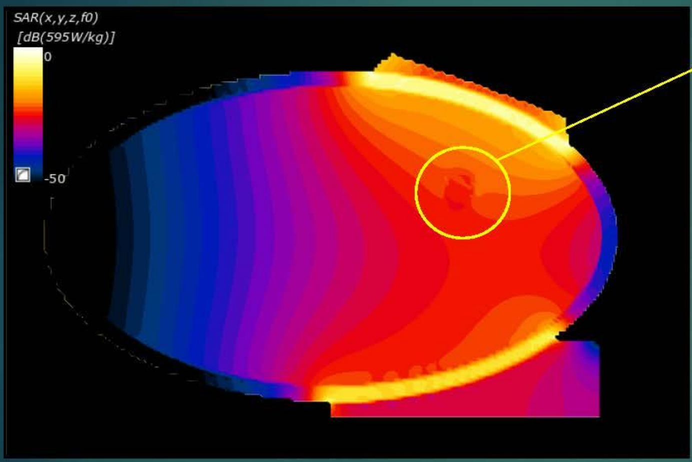
Model 4

Table 3. The results of the final (4th) model.

Model	Number of electrodes	SAR^{max} (local) in tumor [W/kg]	SAR^{max} (local)x100 [(W/kg)/100Wabs]
4th	2	2.98	0.78

The Final Model

25



SAR distribution in the 4th model.

The Final Model

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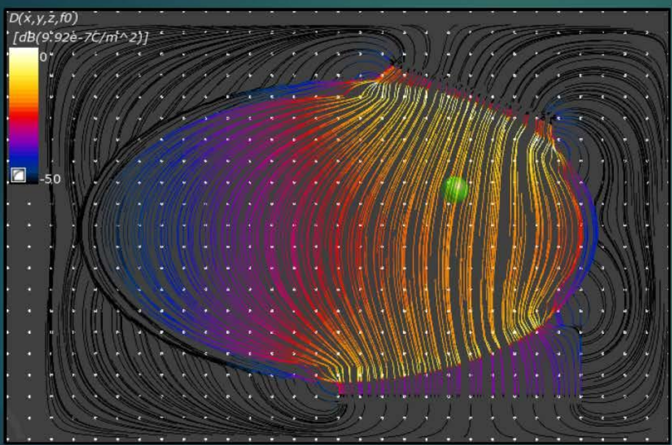

Electric field lines in the 4th model.

Computational Study - Thermal Analysis

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- Having analyzed all those models, the most efficient was the last one. This particular structure and placement of the electrodes results in better distribution of the electric field and maximizes SAR in the tumor region. Thus, the thermal analysis was made for the final (4^{th}) model.

Table 3. Thermal properties of the different parts of the model.

Body Part	Specific heat capacity (J/kg/K)	Thermal Conductivity (w/m/K)	Heat generation rate (W/kg)	Blood perfusion rate (ml/min/kg)
Muscle	3421.2	0.49	0.90	36.73
Fat	2348.3	0.21	0.50	32.70
Tumor	4181.3	0.56	0	0

Hasgall PA, Di Gennaro F, Baumgartner C, Neufeld E, Lloyd B, Gosselin MC, Payne D, Klingenböck A, Kuster N, "IT'IS Database for thermal and electromagnetic parameters of biological tissues," Version 4.0, May 15, 2018, DOI: 10.13099/VIP21000-04-0. itis.swiss/database

Computational Study – Thermal Analysis

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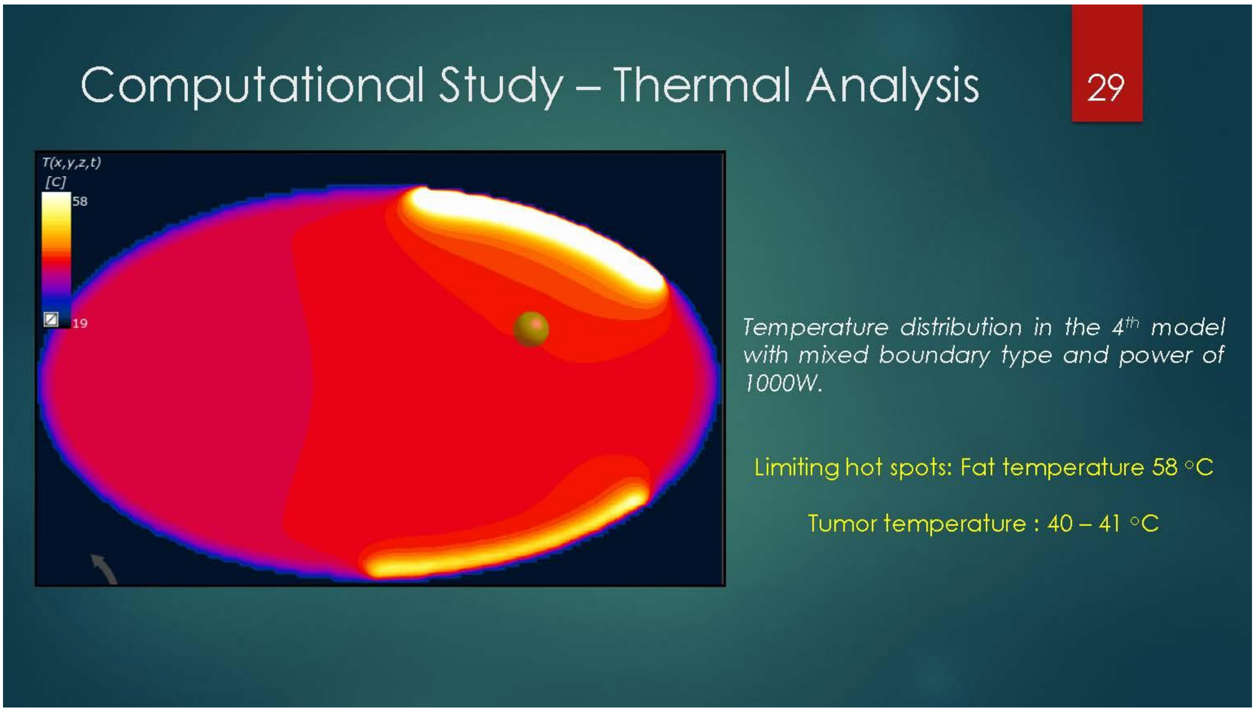
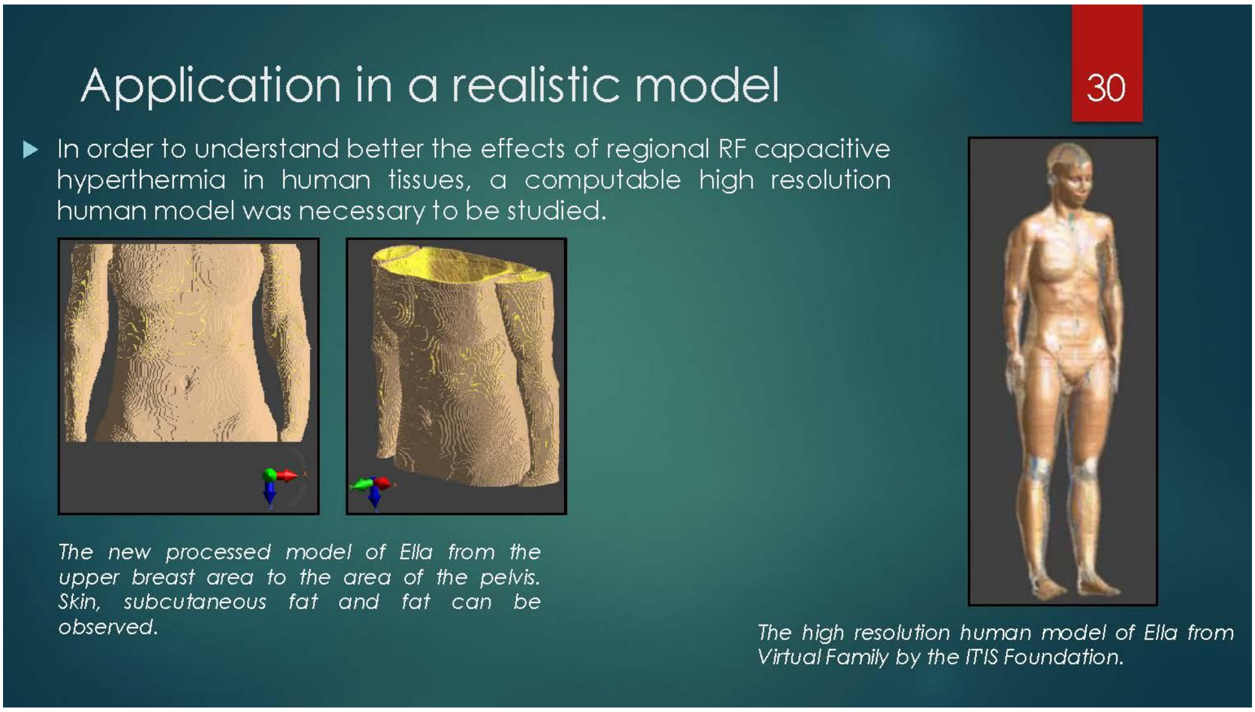
- For the thermal analysis 4 different simulations were created. The simulation ran for two different power settings. The first one was for **400W** total absorbed power and the second one was for **1000W** total absorbed power. The simulation ran for different settings in boundary conditions on the surface of the body. At first we used **Dirichlet** boundary type and afterwards we used **Mixed** boundary type.

Table 4. Temperature in the tumor for different power (W) and boundary settings

Thermal Simulation	Absorbed power (W)	Boundary condition	Tumor temperature (°C)
1	1000	Dirichlet	37-39
2	1000	Mixed	40-41
3	400	Dirichlet	37.7-39
4	400	Mixed	37-38.8


Computational Study – Thermal Analysis
29
T(x,y,z,t)
[C]
58
19
Temperature distribution in the 4th model with mixed boundary type and power of 1000W.
Limiting hot spots: Fat temperature 58 °C
Tumor temperature : 40 – 41 °C


Application in a realistic model
30
In order to understand better the effects of regional RF capacitive hyperthermia in human tissues, a computable high resolution human model was necessary to be studied.
The new processed model of Ella from the upper breast area to the area of the pelvis. Skin, subcutaneous fat and fat can be observed.
The high resolution human model of Ella from Virtual Family by the IT'IS Foundation.

Application in a realistic model

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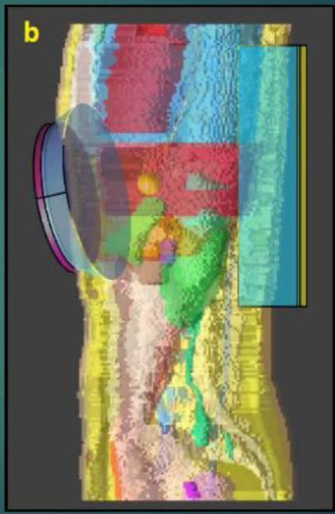

The whole structure of the model with the electrodes and water boluses. a) A front view of the model b) A side view of the model

Application in a realistic model

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- **Table 5.** Dielectric properties of the realistic model Ella

Body part	Density ρ (kg/ m^3)	Electric Conductivity σ_e (S/m)	Relative permittivity ε'
Muscle	1090.4	0.62	138.4
Liver	1078.7	0.33	181.2
Subcutaneous fat	911	0.05	25.3
Tumor	1078.7	0.76	181.2
Skin	1109	0.23	285.2

Hasgall PA, Di Gennaro F, Baumgartner C, Neufeld E, Lloyd B, Gosselin MC, Payne D, Klingenböck A, Kuster N, "IT'IS Database for thermal and electromagnetic parameters of biological tissues," Version 4.0, May 15, 2018, DOI: 10.13099/VIP21000-04-0. itis.swiss/database

Application in a realistic model

33

- **Table 6.** Thermal properties of the realistic model Ella.

Body Part of Ella	Specific heat capacity (J/kg/K)	Thermal Conductivity (w/m/K)	Heat generation rate (W/kg)	Blood perfusion rate (ml/min/kg)
Muscle	3421.2	0.49	0.90	36.7
Liver	3540.2	0.51	9.93	860.4
Subcutaneous fat	2348.3	0.21	0.50	32.7
Tumor [1],[2]	3437	0.56	12	0
Skin	3390.5	0.37	1.64	106.3

Hasgall PA, Di Gennaro F, Baumgartner C, Neufeld E, Lloyd B, Gosselin MC, Payne D, Klingenböck A, Kuster N, "IT'IS Database for thermal and electromagnetic parameters of biological tissues," Version 4.0, May 15, 2018, DOI: 10.13099/VIP21000-04-0. itis.swiss/database

We wanted a primary tumor (not metastasis) in the liver, we left all of its properties (dielectric and thermal) unaffected and changed only the electrical condUntivity to 0.76 S/m (liver cancer).

[1] *Dielectric properties of VX-2 versus normal liver tissue. S.R. Smith, K.R. Foster, and G.L. Wolf,. 1986, Vols. BME-33.*
[2] *Zoi, Sivva. Computational study of capacitive hyperthermia with realistic models . Thessaloniki : s.n., 2019.*

Application in a realistic model

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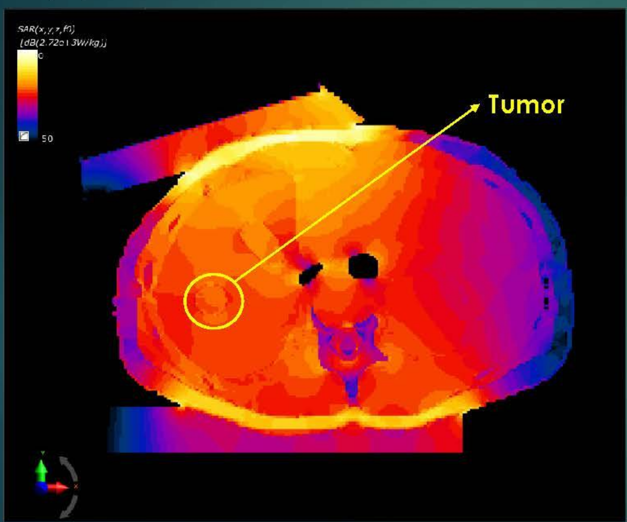

Specific Absorption Rate in Ella with the tumor marked (energy absorption in the tumor region) top view.

Application in a realistic model

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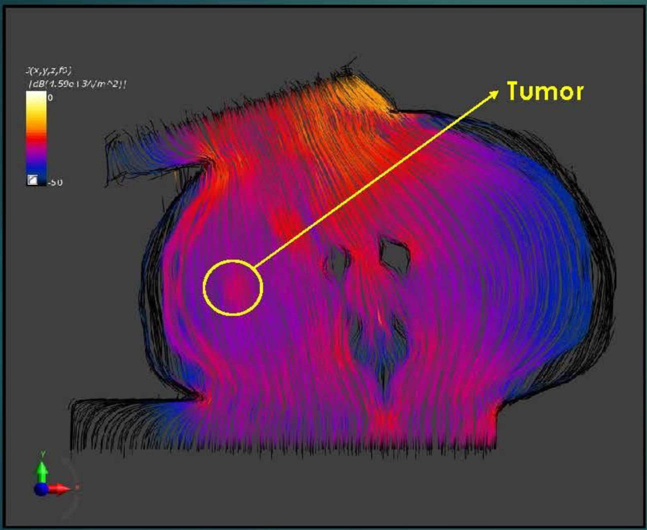

The electric field lines in Ella (top view).

Application in a realistic model

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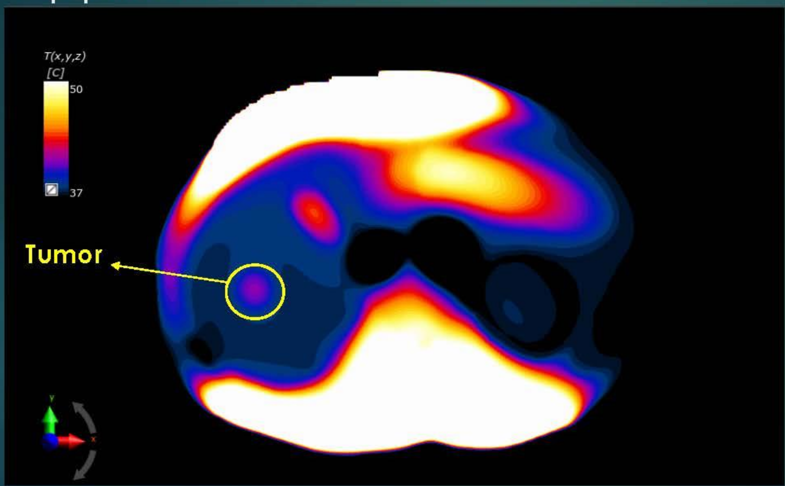

Temperature distribution in the realistic model of Ella (top view).

Temperature in the tumor region ranges between 41.5 and 42 °C.

Conclusions

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- Treatment planning is necessary in order to :
  - Increase power distribution inside the tumor region
  - Predict hot and cold spots
- Results obtained, concern only these particular homogenous models. They may change depending on the location, size and shape of the tumor.
- The optimum result occurred in the last homogenous model in which we had the maximum local SAR per 100 Watts of absorbed power.
- Through the electrical simulations it was confirmed that the number and size of the electrodes induce differences in electric field distribution thus in SAR and power distribution in the models.
- The structure and placement of the electrodes can be used in Ella but further investigation is necessary to be made in order to achieve the optimum result.

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Thank you for your attention