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Coupled Electromagnetic and Thermal Modeling of Microwave Tissue Processing

Iman A Hassaballa[*1], Osama A Hassan[2], Ahmed H Kandil[3], Ahmed M El Bialy[4]

[*1] Systems and Biomedical Engineering Department, Faculty of engineering, Cairo University, Egypt

[2,3,4] Systems and Biomedical Engineering Department, El Shorouk Academy, El Shorouk, Egypt

imanhassab@yahoo.com

Abstract

This study deals with 3D finite element modeling of microwave tissue processing using Comsol software 4.0. Maxwell's equations are coupled with heat conduction equation to determine electromagnetic field distribution and temperature profile within tissue sample in a reagent inside a domestic microwave oven. The microwave power generation term is calculated. Also, temperature distribution obtained is compared with experimental point measurements recorded in the centre of the tissue using a shielded K type thermocouple. Good agreement is found between numerical and experimental data. The effect of size of both reagent and tissue as well as tissue type on microwave heating patterns within tissue sample is investigated. Studies shows that the reagent volume has greater effect than other factors. The results of the study is considered as a basic foundation for development of coupled electromagnetic thermal models of microwave heating of tissue specimens. The model assists in choosing appropriate process parameters for achieving uniform temperature distribution within tissue specimen.

Keywords: Microwave tissue processing; microwave heating; modelling; finite element; electromagnetic field; temperature profile, model validation.

Introduction

Traditional overnight tissue processing has been the standard for many years. The routine work of fixation, dehydration, clearing, impregnation and embedding has been carried out using automated tissue processors. However, this technique suffers from delaying processing time to 8 hours or longer, utilization of toxic reagents such as formalin and xylene, and degradation of nucleic acid [1]. Recently, the use of microwave technology in pathological labs highlights the issue of productivity, creativity and achievement. Microwave tissue processing has been introduced in pathological labs by Boon and Kok in 1985 [2]. Microwaves relies on the dielectric heating mechanism to heat dipolar molecules such as water molecules and polar side chains of proteins. Heat produced inside dielectric reagent and tissue is responsible for accelerating the diffusion of reagent in and out of specimens and denaturation of proteins [1]. Unlike conventional heating, microwaves heat the sample volumetrically where the electromagnetic wave that penetrates the surface is converted into thermal energy within the sample. Domestic microwave ovens were used for carrying the steps of tissue processing where the solutions are brought in and out of microwave oven as many times as the number of steps applied. The main problem facing such ovens is the non uniformity of the field and heterogeneous temperature distribution inside the heated sample. Efforts have been conducted to enhance the uniformity of wave and reducing processing time using additional features such as mode stirrers or fans or combining microwave with other assisted methods.

Regarding food products, many researches try to understand the various factors that affect the uniformity of microwave heating, food shape [3, 4], size [5], dielectric properties of food [3,6], location of food on a turntable [7], and microwave power and cycling [8]. The effect of geometry, size of the sample and the polarization of the wave (TE, TM) have been investigated by Ayappa et al. [9]. Ohlsson and Risman [10]observed that the core centre is the most heated area in spheres and cylinders. Others studied the effect of dimensions of cylindrical samples on the microwave power absorbed [11,12]. Pandit [13] studied the temperature rise in rectangular and cylindrical shaped potatoes. Campanone and Zaritzky [14] conducted a finite difference mathematical model to estimate temperature profile for different geometries. Such individual efforts are subjective and related to specific oven and specific heating material. The lack of standardized procedures and non uniformity of the wave are the main challenge of such studies.

Reports of microwave tissue processing were concerned with comparison of microwave

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assisted tissue processing to routine tissue processing[1,2]. Modeling of biological tissues subjected to microwave irradiation has gained quiet concern in some fields such as Hyperthermia or tissue ablation. On the other hand, the model that actually simulates the behavior of microwave-tissue interaction and impact of process parameters on microwave heating of tissue samples inside a microwave oven is absent.

Studying the factors affecting microwave heating process and modelling the behaviour and interaction of microwaves with tissues is the crucial part of the research. The objective of the current work is to implement a combined electromagnetic and heat transfer model to predict electromagnetic field distribution and temperature profile in pathological tissue specimens immersed in a reagent inside a domestic microwave oven cavity. The microwave heating process is modelled using Comsol 4.0 based on FEM to solve Maxwell's equations and heat conduction equation in three dimensions. Tissue and reagent properties are kept constant. The model is experimentally validated by measurements of point temperatures in the centre of tissue sample using a K type thermocouple probe. The probe is connected to laptop via a USB cable for online temperature recording. The effect of size and type of tissue sample and reagent volume on microwave heating pattern in tissue sample is investigated. The main aim is to adjust the appropriate process parameters suitable to achieve uniform heating patterns inside the tissue sample. Thus avoiding tissue overheating or damage. This model can assist the pathologist in proper implementation of the steps of tissue processing at a low economical cost. This results in rapid and optimum tissue preparation preserving tissue constituents for further microscopic examinations.

Material and Methods

Problem Formulation

Definitions

The chosen microwave oven is MY20P Black and Decker connected to 900 W, 2.45 GHz microwave source via a rectangular waveguide. The dimensions of the feeding waveguide are 4×7.5×1 cm and is excited in the TE_{10}. It is placed at a distance of 10 cm high in z direction, 30.5cm in x direction and 11.75cm in y direction. The dimensions of the cavity is 30.5× 31× 19.2 cm., There is a cylindrical glass turntable located at the centre of the cavity. The glass turntable is 24.5 cm in diameter and 0.6 cm thick. It is placed with a 0.2 cm airspace to the cavity bottom. The modeled sample is a tissue specimen of dimensions 1.5× 1.5 × 0.3 cm (x, y, z) located at the centre of the cavity at a distance of 3.05 cm high from the glass plate. The tissue sample is immersed in a reagent which takes the shape of container. Ethanol is used as the modeled reagent. The dimensions of reagent are 3.9 ×4 ×X 6.67 cm (x, y, z). It is located at the centre just above the glass plate. The schematic diagram of the microwave oven model is shown in Figure 1. The thermal and dielectric properties of heated materials are shown in Table 1. The relative permeability of all materials is the same as free space (μ=1). Symmetry is utilized by simulating only one half of the problem. The symmetry cut is made vertically passing through the centre of the tissue, reagent, oven, turntable and waveguide. The input power is set to 100 W. The initial temperature is 25°C. In order to analyze the process of microwave heating of tissue sample, change in thermal and dielectric properties of tissue & reagent is not considered. Besides, heat transfer by natural convection in reagent is neglected.

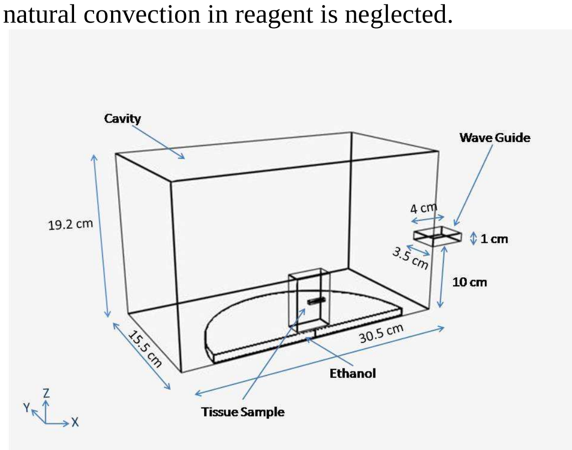

Figure 1: Schematic diagram of microwave oven model

Table 1: Input parameters used in simulation

Parameter	**Value**	**Source**
Air		
Dielectric constant	**1**	*
Electrical conductivity (s/m)	**0**	
Breast tissue		
Relative permittivity	0.4	[29]
Electrical conductivity (s/m)	9	
Thermal conductivity (w/m k)	0.306	[30]
Density (kg/m^3)	1069	
Heat capacity (J/kg k)	2279	
Liver tissue		
Relative permittivity	43	[31]
Electrical conductivity (s/m)	1.69	
Thermal conductivity (w/m k)	0.497	
Density (kg/m^3)	1030	
Heat capacity (J/kg k)	3600	
Stomach tissue		
Relative permittivity	62.2	[31]
Electrical conductivity (s/m)	2.21	
Thermal conductivity (w/m k)	0.527	

Density (kg/m^3)	1050	
Heat capacity (J/kg k)	3500	
Glass		
Relative permittivity	2.55	*
Electrical conductivity (s/m)	0	
Ethanol		
Relative permittivity	10.1-J*9.6	[32]
Electrical conductivity(s/m)	$1.35e^{-11}$	[33]
Thermal conductivity (w/m k)	0.171	[34]
Density (kg/m^3)	789	
Heat capacity (J/kg k)	2440	
Copper		
Dielectric constant	1	*
Electrical conductivity (s/m)	$5.998e^{7}$	
Density (kg/m^3)	8700	
Thermal conductivity (w/m k)	400	
Heat capacity ((J/kg k)	385 e^{-11}	

Equations and boundary conditions

Electromagnetic analysis

Maxwell Time harmonic Maxwell's equations are solved to determine the electromagnetic field distribution inside the microwave oven. For a plane wave propagating in TE_{10} mode, the following equation is utilized:

$\nabla\times(\mu^{(-1)} \nabla E) - (\epsilon_r - j\sigma/(\omega\epsilon_0))k_o^2 E = 0$ (1)

Where E is the electric field intensity, μ is relative permeability, ϵ_r is relative permittivity, σ is electrical conductivity, $\epsilon_o = 8.854\times [10]^{(-12)}$ F/m is the permittivity of free space, $\omega = 2\pi f$ is the angular frequency, $k_o = \omega/c$ where c is the speed of light in vacuum

Boundary conditions

- Symmetry cut is a perfect magnetic conductor and a mirror image for electric field. It has the boundary condition: n x H = 0 (2)
- The walls of oven and waveguide are made of copper and are represented by impedance boundary condition with small resistive losses
- Port condition is applied at the feeding side of the waveguide having a propagation constant β

  $\beta = 2\pi/c \sqrt{(\gamma^2 - [\gamma_c]^2)}$ (3)

  where γ is frequency, γ_c is cut off frequency
- Continuity boundary condition applied at the interior boundary between reagent and tissue sample and is represented by

  $n.(D_1-D_2)=0$ (4)

It specifies that the normal component of the electric displacement is continuous across the boundary.

Absorbed power source calculation

The electric field determined from Maxwell's equations are used to calculate the volumetric power absorbed by the heated sample using the following equation:

$Qv = 2\pi f\epsilon_o \epsilon'' |E|^2$ (5)

where Qv is power absorbed per unit volume (W/m^3), f is frequency (Hz), and E is electric field strength within the sample (V/m).

Heat transfer analysis

Heat transfer in tissue sample is governed by heat conduction equation. The heat generation source calculated from the previous equation is used as an input term in the heat equation . Finally the temperature profile inside the tissue sample is determined.

$\rho c_p \partial T/\partial t = \nabla\cdot(k \nabla T) + Q$ (6)

Q is the internal heat generation source term (w) and represents the amount of power dissipated by heated sample due to dielectric losses, k thermal conductivity measured in (w/m k), ρ is density (kg/m^3), c_p is specific heat (J/kg k), T is temperature (°c) and t is time (sec)

Boundary conditions

- Heat flux continuity is specified at the interior boundaries between reagent and tissue sample

  $n . (k_1 \nabla T_1 - k_2 \nabla T_2) = 0$ (7)
- Thermal insulation is utilized at all other boundaries

  $n \cdot \nabla T = 0$ (8)

Finite element analysis

Maxwell's equations and heat transfer equation are solved using Comsol 4.0 multiphysics software based on finite element method. Finite element method (FEM) has been known for its flexibility and capability of handling irregular and complex shaped objects. FEM has been used to predict electromagnetic field distribution [21,22] and to analyze coupled electromagnetic thermal problems [9,22]. Since the heated sample's thermal and dielectric properties are constant, the problem is linear and Maxwell's equations can be solved independent of the heat equation.

Model validation

To validate the model in this study, point temperature measurements in the centre of the tissue sample are recorded during 5 min of microwave heating. A K type insulated braided wire type thermocouple 1m (40") (Omega Company, model

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SC-GG-K-30-36) connected to a data logger (Model HH806AU) was used for temperature measurements. The probe is shielded with three layers to prevent arcing. A primary layer is an insulator. The second layer is an aluminum foil to reflect microwaves. The last layer is made of Teflon that is transparent to microwaves & gives probe more support. The thermocouple enters the cavity through an air circulation opening at the left side of the oven after being widened to 0.7 cm. The probe is twisted to make a right angle at the middle of oven & dipped into tissue centre. The thermocouple probe is connected to a laptop via USB cable for continuous data collection. The recorded temperature values of each experiment give an indication of the temperature profile inside the tissue centre.

Result

Effect of tissue thickness on temperature distribution inside tissue sample

The effect of tissue thickness on microwave heating of liver tissue specimen is tested by varying tissue thickness to 0.2 cm, 0.4 cm and 0.6 cm using three models. The total heat source, numerical versus experimental temperature profile in the centre of liver sample and temperature contour plot in the mid XY plane passing through the centre of tissue during the first 60 seconds of microwave heating are evaluated.

Total heat source

As shown in Table 2, as the tissue thickness increases, the amount of heat absorbed increases.

Table 2: Total heat source for different tissue thicknesses

Tissue thick.	0.2cm	0.4cm	0.6cm
Total heat source	0.066	0.1445	0.3918

Predicted temperature profile versus experimental ones

Figure 2 shows experimental and numerical temperature distribution in the centre of liver tissue sample for different tissue thicknesses after 60 sec of microwave heating. At 60 sec for example, the numerical temperature values for liver tissue thicknesses of 0.2 cm, 0.4 cm and 0.6 cm are 36.8784 ºC, 33.7852 ºC and 32.5336 ºC respectively. Also, the corresponding experimental values for cases of 0.2 cm, 0.4 cm and 0.6 cm are 32.1 ºC, 31.7 ºC and 30.2 ºC. According to results, it is clear that as tissue thickness increases, the temperature profile inside the centre of liver tissue decreases. Comparing experimental temperature profile against predicted ones, the results show that there is a good agreement between experimental and numerical results. P values between experimental and simulated data are 0.957004 for 0.2 cm, 0.977169 for 0.4 cm and 0.537475 for 0.6 cm. Statistical P values indicates no significant difference between results.

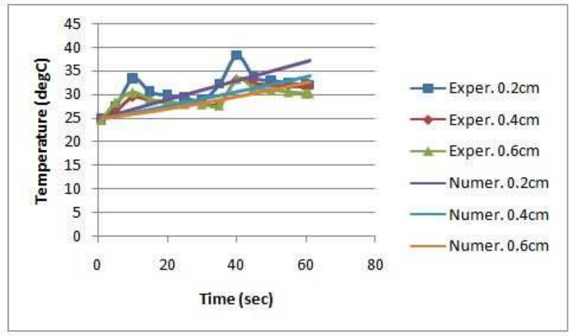

Figure 2: Experimental & numerical temperature distribution in the centre of liver tissue for tissue thicknesses 0.2cm, 0.4cm, 0.6cm during 60 sec of heating

Temperature contour plots are shown in Figure 3 after 60 sec of microwave heating in XY plane at Z= 3.851 cm passing through the mid-plane of Liver sample in ethanol for the three different thicknesses. As shown, the temperature pattern is the same for different thicknesses with more heating towards the left and right edges. Thus the minimum values are found at the centre and the maximum temperature values are confined at the peripherals. The gap between temperature values increase with increase in tissue thickness. That is to say the minimum values are decreased and maximum values are increased with increase in tissue thickness. For example, the differences between maximum and minimum temperature values for tissue thicknesses of 0.2 cm, 0.4 cm and 0.6 cm are 8ºC, 10ºC and 13ºC respectively. Thus small tissue thickness constitutes more uniform temperature distribution.

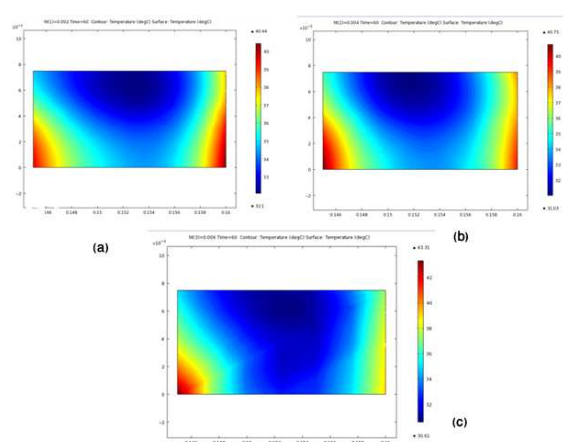

Figure 3: Temperature contour plot at 60 sec of microwave heating in XY plane at Z= 3.851 cm

passing through the mid-plane of liver tissue sample of thicknesses (a) 0.2cm, (b) 0.4cm & (c) 0.6cm

Summing up the results, it is shown that as tissue thickness increases, the amount of heat absorbed inside the tissue sample increases. However, the temperature profile in the centre of the tissue sample decreases. This can be explained by increasing tissue thickness, the rate of temperature rise in the centre is less than that at the periphery. Thus it takes much time to reach equilibrium by the mechanism of heat transfer. However, with small tissue thickness, the heat is distributed uniformly on the whole specimen and the steady state is reached quickly. The results show that small tissue thickness constitutes more even temperature distribution. This agrees with Ayappa [9] who claims that small samples whose dimensions is smaller than the wavelength of radiation in the medium constitutes more uniform temperature distribution.

Effect of reagent height on temperature distribution inside the tissue sample

The impact of ethanol height on microwave heating of liver samples during the first 60 seconds has been investigated. For ethanol volumes of 100 ml and 150 ml, simulated temperature values at centre of both tissue types are compared with experimental results. Besides, the amount of power absorbed and temperature contour plots in the mid XY plane passing through the centre of liver samples are predicted.

Total heat source

Table 3 shows the amount of power absorbed in liver tissue samples for the selected ethanol heights. It is evident that as the height of reagent increases, the amount of microwave power absorbed inside the tissue sample decreases.

Table 3: Total heat source for different reagent heights

Total heat source (w)	100 ml	150 ml
Liver tissue	0.0651	0.0125

Predicted temperature profile versus experimental ones

Figure 4 (a) shows the measured & numerical temperature values in the centre of liver tissue during the first 60 sec of microwave heating. Observing simulated results, the temperature of tissue sample decreases as the ethanol volume increases. At 60 seconds, for example, the temperature values in the centre of liver sample immersed in 100 ml and 150 ml ethanol are 34.5644°C and 29.0518°C respectively. As for experimental results, the recorded temperature values in tissue centre at 60 second are 32.2°C and 31.1 °C for ethanol volume of 100 ml and 150 ml. The experimental saw tooth pattern is mainly due to on/off nature of magnetron. discrepancies between experimental and numerical data can be due to on/off nature of magnetron. During on periods, temperature increased dramatically for a couple of seconds according to duty cycle of magnetron. However, during off periods, thermal diffusion tends to stabilize temperature differences across tissue sample. Expected errors can occur due to misalignment of probe or lack of probe sensitivity. Also, experimental temperature profiles are compared against predicted ones. The corresponding P value for ethanol volume of 100 ml and 150 ml are 0.210953 and 0.730051. These values indicate no significant difference ($P > 0.05$) between simulated and experimental results.

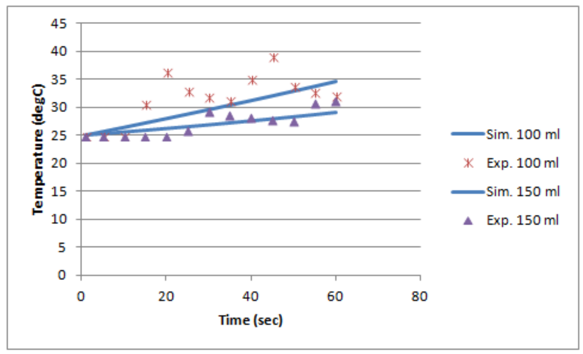

Figure 4: Simulated and experimental temperature distribution in centre of Liver tissue for ethanol heights of 6cm, 8cm & 10cm during first 60 sec of microwave heating

Temperature contour plot

Temperature contour plots are shown after 60 sec of microwave heating in XY plane at Z= 3.851 cm passing through the mid-plane of liver samples in ethanol of volume 100 ml and 150 ml in Fig. 5(a) and (b) respectively. It is observed that as the volume of reagent decreases, the gap between temperature values in the contour plot of tissue samples increases. At ethanol height of 100 ml, the temperature range in the mid plane of liver sample is 32.32- 40.1°C. However, at ethanol volume of 150 ml, the temperature ranges are 28.65- 34.05°C . It is characterized by lower heating rate and more uniform temperature distribution. The temperature pattern for both cases are homogeneous in the middle with slightly more heating towards the left and right edges.

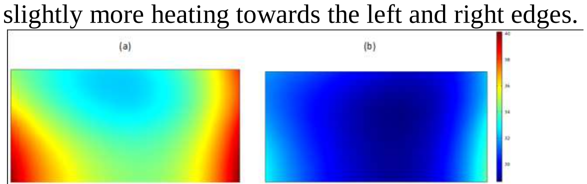

Figure 5: Temperature contour plot after 60 sec of microwave heating in XY plane at Z= 3.851 cm passing through the mid-plane of liver tissue sample with reagent height of (a) 100 ml & (b) 150 ml respectively

Thus the volume of reagent influences to a great extent the temperature values inside a tissue sample . For small reagent volume, more heat are transferred across the reagent tissue interface. Accordingly, the heating rate inside the tissue rises up quickly. Besides, the temperature profile in the tissue sample is characterized by non homogeneity and differences between inside and borders. However, larger volumes of reagent require larger time to heat up. Thus the heat transferred across the boundary is less. The tissue is characterized by lower heating rate and uniform temperature distribution.

Effect of tissue type on temperature distribution inside tissue sample

The impact of dielectric properties of tissue specimens on microwave heating are observed through the study of amount of heat absorbed, temperature distribution in tissue's centre and temperature profile in an XY plane passing through the centre of the tissue sample during the first 60 seconds of microwave operation.

Total heat source

Table 4 shows the amount of heat absorbed by different tissue specimens. It is clear that stomach sample has the highest total heat source of 0.0726 W. This is due to its high dielectric constant (ε= 62.2). This is followed by liver sample (ε= 43) whose total heat source is 0.065W. Finally, breast tissue (ε= 9). has a total heat source of 0.0364 W.

Table 4: Total heat source for different tissue types

Tissue Type	Breast	Liver	Stomach
Total heat source	0.0364	0.0651	0.0726

Predicted temperature profile versus experimental ones

Figure 6 shows experimental and numerical temperature distribution in mid XY plane passing through the centre of breast, liver and stomach tissue samples immersed in an ethanol reagent after 60 sec of microwave heating . It is clear that within the boundaries of the model, there are small discrepancies between the temperature values in different tissue samples. At 60 sec, for example, the numerical temperature values in the centre of breast, liver and stomach samples are 33.9767, 34.5644 and 35.1318 respectively. Concerning experimental data, the results show minute variations among different tissue types. It is hard to discriminate between each type. There is no significant difference between the results. The corresponding P values between numerical and experimental data for liver, breast and stomach are 0.137146, 0.632475 and 0.184878 respectively.

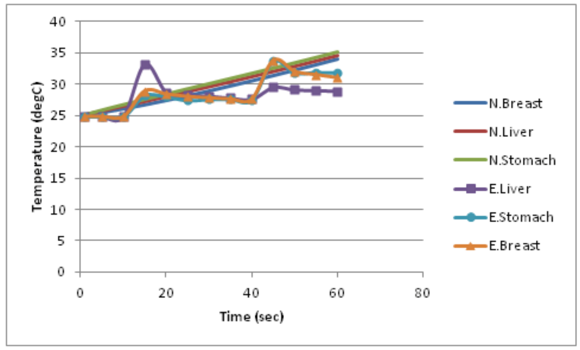

Figure 6: Experimental & numerical temperature distribution in the centre of liver tissue for breast, liver and stomach samples during 60 sec of heating

The temperature contour plot in the mid XY plane passing through the centre of tissue for different tissue types after 60 sec of heating is also determined, The heating pattern and temperature rise is noticed to be the same for the three tissue types. The heating profile is characterized by uniform heating at the centre with more heating towards the left and right borders. The temperature values range between 32.23- 40.7 °C.

The results reveal that the heating rise inside different tissue types are much alike. tissue type doesn't have a major contribution in heating process. This is due to the fact that microwave absorption inside the tissue is accompanied with thermal diffusion across the tissue- reagent boundaries and conductive heat transfer within the tissue sample. Thermal equilibrium is reached when heat transferred across the sample is equal to heat inside the tissue sample. The factor that mainly affects microwave heating is mainly the volume of the reagent.

Conclusions

A model was developed to simulate microwave heating of tissue samples in a domestic microwave oven by coupling electromagnetic and thermal phenomena. The proposed model allows better understanding of microwave interaction with tissue. The results show that immersion of a tissue in a liquid changes the temperature pattern within the tissue due to energy absorption in the liquid as well as the mechanism of heat flow at the boundaries.

Reagent volume as shown is the major contribution affecting microwave absorption inside the tissue. Adjusting the factors affecting microwave heating of tissue specimens avoids tissue overheating and improves temperature uniformity within the tissue sample. This preserves tissue constituents and maintains tissue in a life like status for further histologic evaluations.

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