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Numerical modeling of continuous hybrid heating of cryo-preserved tissue

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Abstract

This study developed a numerical simulation of a hybrid microwave heating process that may be used to produce high heating rates for warming cryo-preserved biological tissue. A finite difference time domain (FDTD) technique was used to model the electric field distribution within a single-mode microwave cavity. Field strength data allowed power deposition to be computed and the control volume method was used to solve the energy equation. Temperature dependence of dielectric properties was simulated through an iterative process. As an illustrative example of the numerical model, a hybrid heating process was simulated. This simulation illustrated that hybrid heating schemes can be used to produce high rates of heating with increased uniformity of the temperature distribution and reduced incidences of local hot spots. © 1998 Elsevier Science Ltd. All rights reserved.

Nomenclature

a length of the cavity [m]
b width of the cavity [m]
c height of the cavity [m]
C velocity of light in free space [m s^{-1}]
C_p specific heat of the processed beef tissue [J kg^{-1} K^{-1}]
E_z z-component of the electric field [V m^{-1}]
E_{rms} root mean square value of the electric field [V m^{-1}]
h convective heat transfer coefficient [W m^{-2} K^{-1}]
H_x x-component of the magnetic field [A m^{-1}]
H_y y-component of the magnetic field [A m^{-1}]
k thermal conductivity of the processed beef tissue [W m^{-1} K^{-1}]
q microwave power density [W m^{-3}]
T temperature of the processed beef tissue [K]
T_∞ temperature of surroundings [K]
V y component of the velocity [m s^{-1}]
w width of the sample [m].

Greek symbols

Δt time step for the electromagnetic field computation [s]
Δx the x-direction width of the Yee cell in electromagnetic field computation [m]
Δy the y-direction width of the Yee cell in electromagnetic field computation [m]
ε' relative dielectric constants of the processed dielectrics [F m^{-1}]
ε'' relative loss factor dielectric constants of the processed dielectrics [F m^{-1}]
ε_0 dielectric constants of the air [F m^{-1}]
μ permeability in free space [H m^{-1}]
ρ density of the processed beef tissue [kg m^{-3}]
σ absorptivity of materials to the microwave field [Ω m^{-1}].

1. Introduction

Practical methods for vitrifying biological tissues would provide inestimable benefits to the field of medicine. In the context of cryopreservation, vitrification typically refers to the avoidance of ice crystals with sizes large enough to cause cell damage [1, 2]. The chief appeal of vitrification as an approach to cryopreservation is that it avoids many of the types of cellular damage due to the formation of ice crystals. Since molecules of vitrified water do not undergo bulk reorganizations into crys-

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talline forms it has been widely speculated that vitrification is actually innocuous to biological tissues.

All practical cryopreservation protocols require biological tissues to survive two perilous processes, cooling down to cryogenic storage temperature and the subsequent rewarming. In many respects the threats to cell viability are greater during the rewarming phase [3]. This is particularly true if the approach used during the cooling process produced a non-equilibrium phase (i.e. a vitreous solid). The prevailing view of vitrification is that numerous ice nuclei form during the cooling process but then find themselves in an environment too viscous to permit detectable growth. These nuclei are preserved in the vitreous solid until the sample is rewarmed. During the rewarming process these nuclei may grow at extremely rapid rates into damaging ice particles. Typically, vitrified aqueous solutions present in biological systems will begin to reorganize into crystalline forms once the temperature is raised to about -40°C [1]. The traditional approach to minimizing this problem is to rewarm the sample as quickly as possible. This minimizes ice crystal damage by traversing the range of temperatures where there is both a significant thermodynamic deriving force toward crystallization and a significant degree of molecular diffusion. Unfortunately, avoiding formation of ice during rewarming would require heating rates that are very difficult to achieve. The chief impediment is that biological tissues have relatively low thermal conductivities and high specific heats. Moreover, care must be taken not to overheat the tissue. Since cell death occurs at around 40°C this places a maximum on the temperature gradient which can be imposed in order to produce conductive heating of the tissue.

The use of microwaves for heating offers some significant advantages over conventional heating methods. Since heat is generated volumetrically, the low thermal conductivity of biological materials is not so problematic. Additionally, with proper design, microwaves can deposit energy at very high rates [4]. Although these advantages have long been recognized there has been little progress toward widespread application of microwave heating processes to avoid devitrification. Perhaps the greatest disadvantage to the use of microwaves is that heating processes require very careful design to achieve the intended outcome and avoid undesired effects. One such undesired effect is the occurrence of thermal runaway, which arises due to the temperature dependence of dielectric properties influencing the deposition and dissipation of the electromagnetic energy. Thermal runaway is a localized, nearly exponential, increase in temperature [5], which arises due to the temperature dependence of dielectric properties. Uncontrolled thermal runaway is a significant problem since local areas of tissue may be inadvertently killed by overheating, and meanwhile, the remainder of the tissue may be damaged by ice crystal growth since these regions would experience considerably reduced heating rates. Previous works [6–8] have dealt with the occurrence of thermal runaway by pulsing the microwave field on and off. This approach evens out the temperature distribution by allowing heat to dissipate by conduction through the tissue but also greatly reduces the maximum heating rate which can be achieved. For this reason such an approach to controlling the occurrence of local hot spots would not be optimal for rewarming vitrified biological tissues.

In some respects, however, the phenomenon of the occurrence of thermal runaway is precisely what cryobiologists desire. With rapidly increasing temperature changes it may be possible to outrun the crystallization process and thereby avoid the cell damage induced by ice. What is needed is a means of developing a warming process that can take advantage of the beneficial effects of thermal runaway while avoiding its dangers. In order to achieve this it will be necessary to gain further control over the warming process, either by introducing additional parameters to control the process or by the use of numerical simulations to aid in process design. In this study both of these strategies were used. A novel scheme for warming vitrified tissues was proposed and a numerical model of this scheme was developed in order to determine appropriate parameters which result in rapid uniform heating.

The warming scheme proposed in this study involves the use of a continuous hybrid microwave heating process. In the present context, hybrid heating refers to the combination of volumetric energy deposition by microwaves and convective heat transfer [9] from a fluid at the surface of the biological material. This combination of heating mechanisms has the potential to produce warming rates which heretofore were unobtainable. An additional benefit of such a hybrid-heating scheme is the introduction of additional parameters, such as the velocity V of the continuously moving material, the heat transfer coefficient h, and surrounding temperature T_{∞}, which can be used to improve control of the heating process. When volumetric microwave heating is combined with convective surface heating there are greater opportunities for controlling the warming process so more uniform temperature profiles are possible. Since this decreases perturbations in the temperature distribution the likelihood of thermal runaway is decreased. Moreover, hybrid-heating schemes may permit a reduction in microwave power while still achieving a high overall heating rate. This has the potential to further reduce incidence of local hot spots.

Unfortunately, thermal runaway is a highly complex and unstable phenomenon. For this reason numerical simulation is the only viable approach to conducting warming process modeling and design. Three factors produce the complexity in modeling microwave-heating process. One is the non-uniformity of the microwave field

[10]. Microwave wavelengths frequently have the same order of magnitude as the dimensions of the material to be heated, which causes large variations of the field strength across the material. The second complication is the distortion of the well-defined electric field for an empty cavity by the presence of dielectric loads. Thirdly, temperature dependence of dielectric properties affects both the electric field distribution and the absorption of microwave energy.

2. Numerical model for heating process

The finite difference time domain (FDTD) method has become the method of choice for modeling electromagnetic fields [11–21]. Reasons for this include the relative simplicity and efficiency of the method (compared with the traditional frequency-domain method). Since interaction of microwave energy with real dielectric materials is non-linear an authentic model of microwave heating should take this into account. Moreover, an accurate model should simulate the manner in which a dielectric material affects the E field as it is being warmed. For most materials, the dielectric properties vary with the temperature. This change can significantly distort the electric field distribution over the course of the heating process. In either case the maxima of the electric field will be shifted. Since this is equivalent to changing the internal heating source terms in the energy equation it is important to include this phenomenon in any model of the heating process.

The development of an iterative scheme to consider coupling of these phenomena provided a significant advance in microwave heating simulation [22]. With this scheme the E field is calculated by standard FDTD methods and then it is used as a source term in the energy equation. The resulting nodal temperature values are then used to estimate appropriate nodal values for the dielectric properties. If these values are significantly different from the values used in the FDTD calculation then the field computations would be repeated using updated dielectric properties.

A physical model of a hybrid microwave heater is depicted in Fig. 1. Microwave energy is fed into the cavity by an antenna located 1/4 wavelength from the end of the cavity. It is oriented in such a way to excite only TE modes. Openings in the sides of the cavity allow a rectangular bar of dielectric material to be moved through the cavity. Cryopreserved materials with this geometry could include narrow strips of skin or an idealized tube containing cell suspensions. Heated air may also be circulated through the cavity in order to produce a convective heat flux into the surface of the material. The microwave resonant cavity considered supports a TE_{410} mode at 2.45 GHz. With this mode field components vary sinusoidally in X- and Y-directions but are uniform in the Z-direction [23]. The introduction of a lossy dielectric may excite perturbations which can lead to formation of other modes and cause variations in absorbed power along the Z-direction. In this study, it was assumed that the relatively small dimensions of the biological tissue combined with its low loss factor, and dielectric constant would lead to a negligible amount of perturbation. In such a case the energy equation source term is independent of Z.

The numerical model developed in this study took advantage of this by collapsing the hybrid heater into the two-dimensional form shown in Fig. 2. The domain in which the electromagnetic field was analyzed included the entire region enclosed by the walls of the resonant cavity. The coordinate system used in describing this field was denoted as XY and the cavity walls were assumed to be perfect electrical conductors. A slab of the lossy dielectric representing the material to be heated spans the cavity. A second coordinate system xy was designed for the purpose of describing the temperature field within the material. In order to model a continuous heating process the material may be moved through the cavity, along the y-axis, with velocity V.

The microwave field within this cavity is defined by Maxwell's equations. The two-dimensional unsteady forms of Maxwell's equations are:

$$\varepsilon\frac{\partial E_z}{\partial t}=\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}-\sigma E_z \quad (1)$$

$$\mu\frac{\partial H_x}{\partial t}=-\frac{\partial E_z}{\partial y} \quad (2)$$

$$\mu\frac{\partial H_y}{\partial t}=\frac{\partial E_z}{\partial x} \quad (3)$$

where ε is permittivity, σ is absorptivity of the microwave energy, and μ is permeability. For an empty resonant cavity with perfectly conductive walls an analytical solution to the Maxwell equations is readily available. One result of this solution is that the conditions for resonance may be described as:

$$f_{\alpha\beta\gamma}=\frac{C}{2}\left[\left(\frac{\alpha}{a}\right)^2+\left(\frac{\beta}{b}\right)^2+\left(\frac{\gamma}{c}\right)^2\right]^{1/2} \quad (4)$$

where $f_{\alpha\beta\gamma}$ is the frequency, α, β and γ describe the mode of resonance, C is the speed of light in free space, and a, b and c are the cavity dimensions in the X-, Y- and Z-directions, respectively. In the case of a lightly loaded resonant cavity equation (4) provides a means for establishing reasonable cavity dimensions and estimating the fundamental mode of resonance. In this study the dimensions of the cavity were selected so as to support a TE_{410} mode at 2.45 GHz in an empty cavity. Such a low mode of resonance is of interest because local regions of the electric field may become extremely strong, leading to rapid and efficient heating of a material placed in these

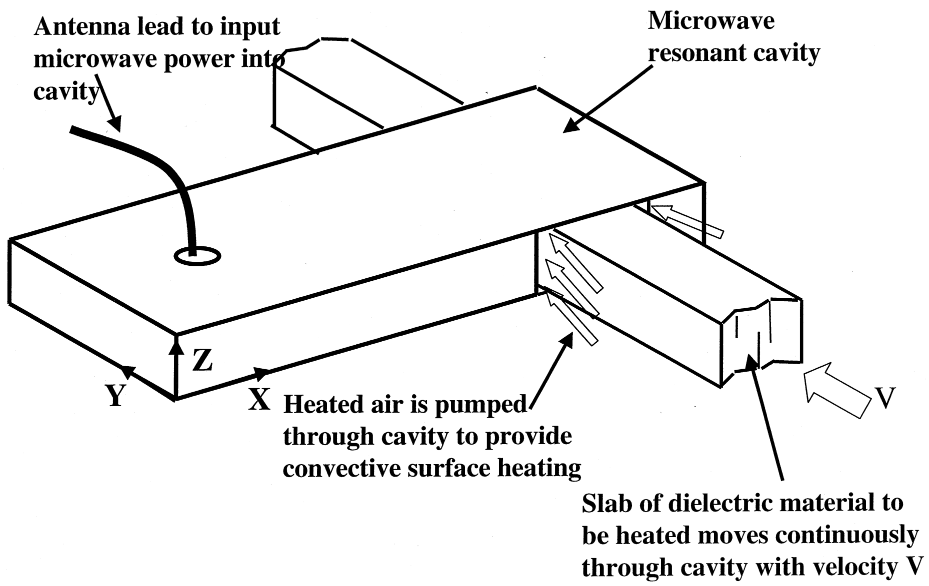

Fig. 1. Schematic diagrams of hybrid microwave heater.

regions. The appropriate cavity dimensions for a 2.45 GHz TE_{104} mode were ascribed to be 0.0865×0.346 m.

The computational domain was divided into an array of 21×321 elementary cells, each containing the local value of E and H. The resulting cell size was small enough to satisfy the Courant stability requirement and significantly exceeded the often quoted constraint of 10 cells per wavelength [24]. The stencil used to discretize space within the resonant cavity is shown in Fig. 3a. It is noteworthy that the$E$ and H components are offset in their locations by one half cell. This staggered grid models Maxwell's curl equations by allowing spatial changes in the E (or H) field components to act as the driving force for the H (or E) field component located midway between. In a similar fashion, transient changes of the H (or E) field may act as a source term for generating the complementary field component. This effect may be modeled by temporally separating the E and H components by 1/2 time step. Figure 3b illustrates how the components are arranged in the time domain. In discretized form equations (1)–(3) become:

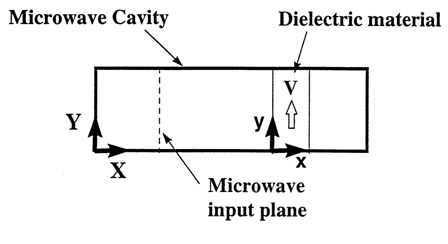

Fig. 2. Two-dimensional domain used for FDTD simulation.

$$E_Z^{n+1}(i,j) = \frac{1-\sigma\Delta t/2\varepsilon}{1+\sigma\Delta t/2\varepsilon} E_Z^n(i,j) + \frac{\Delta t}{(1+\sigma\Delta t/2\varepsilon)\varepsilon\Delta x}(H_y^{n+1/2}(i+1/2,j) - H_y^{n+1/2}(i-1/2,j) - \frac{\Delta t}{(1+\sigma\Delta t/2\varepsilon)\varepsilon\Delta y}(H_x^{n+1/2}(i,j+1/2) - H_x^{n+1/2}(i,j-1/2)) \quad (5)$$

$$H_x^{n+1/2}(i,j+1/2) = H_x^{n-1/2}(i,j+1/2) + \frac{\Delta t}{\mu\Delta y}(E_z^n(i,j) - E_z^n(i,j+1)) \quad (6)$$

$$H_y^{n+1/2}(i+1/2,j) = H_y^{n-1/2}(i+1/2,j) + \frac{\Delta t}{\mu\Delta x}(E_z^n(i+1,j) - E_z^n(i,j)). \quad (7)$$

The appropriate boundary conditions are that the tangential component of the electric field and the normal components of the magnetic field go to zero at the conductive walls. At the interface of the metallic walls and the dielectric material, the boundary conditions require that E_y, E_z, and H_y should disappear. With a TE_{410} wave, these requirements are automatically satisfied due to two reasons. First, the TE_{410} wave has no E_y component, and second, amplitudes of E_z and H_y of this wave are zero at the walls where the dielectric material enters and exits the cavity. For this reason, the enclosure can be modeled as a perfect electrical conductor at the entrance and the exit of the dielectric load. Excitation of the cavity was accomplished by imposing a 2.45 GHz plane polarized source that varies sinusoidally with time. The source was located at $X = 0.043$ m. This location was chosen to coincide with a maximum in the electric field for an empty cavity in order to excite the resonance in the cavity. The use of a two-dimensional model required modification to the means by which microwave energy was input into the cavity. In reality, the antenna lead shown in Fig. 1 will radiate microwaves with a spherical wave front. With an assumption of perfectly conducting walls of the cavity, this spherical wave will travel infinitely in the cavity and its wave front will approach to a plane wave front. For this reason, a plane of excitation was substituted, as shown in Fig. 2.

Using the method of FDTD [10], equations (5)–(7) were solved for each interior node by employing an explicit scheme which marches through both time and space. The FDTD method adopts an explicit approach for two reasons. Firstly, the time dependent Maxwell equations are hyperbolic in nature so that the solution may be more stable. The second advantage is that explicit schemes yield greater accuracy when the time steps are small (around 10^{-12} s), which is certainly the case for radiation in the GHz range. Once the FDTD code has generated a solution for the electromagnetic field it is possible to proceed to the real objective, simulation of the microwave heating process. The energy absorption by a lossy dielectric material in a microwave field is described by

$$q = \sigma |E_{\mathrm{rms}}|^2 \tag{8}$$

where σ is the temperature dependent absorptivity and E_{rms} is the root mean squared value of the electric field at a particular location.

The objective of this hybrid microwave heating process is to warm vitrified biological tissue at a rate great enough to leave insufficient time for crystallization to occur. In other words, the heating process would start with an amorphous solid and end with a liquid. In a successful rewarming process there would be no significant crystallization and therefore no significant entropy change to cause latent heat generation. Such a second order phase change has small variations in thermophysical properties and latent heat releases when compared with freezing or thawing. For this reason, variations in thermophysical properties due to phase change were assumed to be negligible, and the energy equation can be written as:

$$\frac{\partial}{\partial t}(\rho C_{\mathrm{p}} T) = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) - \frac{\partial}{\partial y}(\rho C_{\mathrm{p}} V T) + \sigma |E_{\mathrm{rms}}|^2 \tag{9}$$

where ρ, k, C_{p}, V are the dielectric material density, thermal conductivity, specific heat, and velocity components in the y-direction, respectively. The last term is the microwave-heating source term. For the geometry under consideration the thermal boundary conditions were:

$$T(x,0) = T_0; \quad \partial T/\partial y|_{y=b} = 0;$$
$$q''|_{x=0} = h(T_\infty - T); \quad q''|_{x=w} = -h(T_\infty - T)$$

where b is the width of the cavity and w is the width of the dielectric load. Appropriate values of the convective heat transfer coefficient h where one of the parameters varied in the numerical experiment to produce a desirable hybrid heating process. With the preceding boundary and initial conditions, equations (8)–(12) were solved numerically by using the Control Volume explicit method [26].

In order to realistically simulate the physics of a microwave heating process it is necessary to consider the coupling between the E field and the temperature distribution. The E field clearly affects the temperature due to its function as a source term in equation (9). However, the temperature distribution also influences the electric field distribution through the temperature dependence of material dielectric properties. It is worth noting that a direct, simultaneous solution of the E field and temperature distribution would not produce a practical computer simulation. This is due to the vast difference between the time scales used in these calculations. Stability of the FDTD solution requires time steps on the order of 1 ns, as dictated by the Courant stability requirement [24]. For heating processes the relevant time scale is frequently on the order of seconds or minutes. Herein lies the shortcoming with the direct approach of simultaneously solving the E field and temperature distributions. Such an approach would require marching through billions of time steps in order to simulate a second of heating.

An iterative scheme which circumvents these shortcomings is to solve for the E field within certain time period (54 000 time steps for the field computation) and then calculate the average E_{rms} during this time period. This E_{rms} was treated as constant over one time step for the thermal computation. This E field was then used to determine source term data from which an updated temperature distribution could be calculated. Curve fits of published dielectric data [26] were used to determine dielectric properties as a function of temperature. A routine was written into the program which monitored changes in the dielectric properties from one iteration to another. If the dielectric constant at any node varied by more than 10% the E field was recalculated and a new average E_{rms} value was obtained. The variation of 10% was found to be a reasonable compromise which minimized computational time and still provided consistent results. The updated E_{rms} used as the source for the next thermal computations. There are significant advantages to this approach. Since the temperature dependence of microwave energy absorption is considered it becomes possible to accurately model the important phenomena of thermal runaway. Moreover, this iterative scheme accounts for variations in the E field that occur as a material with temperature dependent dielectric properties is heated.

3. Results and discussion

It is often stated that the greatest limitation of microwave heating is the non-uniformity of the temperature distribution. For this reason, an obvious application of the numerical model developed herein is to determine the design of a workable hybrid heating device which can provide both uniform and rapid warming. It is also worthwhile to illustrate the various aspects of hybrid microwave heating using a resonant cavity. The following results illustrate the highly coupled nature of microwave heating and point out the value of numerical simulation in developing a process which can produce the desired outcome.

The following results were generated by using a curve fit of dielectric properties for beef tissue [26]. Temperature dependence of the relative dielectric constant ε' and the dielectric loss factor ε'' are illustrated in Fig. 4a and b, respectively. It is this strong dependence which makes microwave heating unstable and prone to the occurrence of local hot spots. For temperatures below 0°C the data shown in Fig. 4 actually correspond to frozen tissue. The paucity of published dielectric properties for vitrified tissues have led the authors to assume this data also describes vitrified tissue.

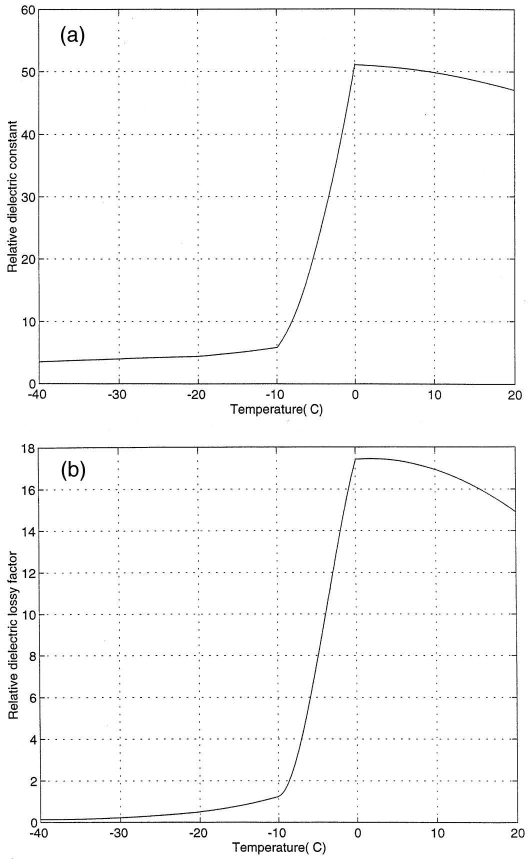

Fig. 4. Dielectric properties of beef muscle tissue.

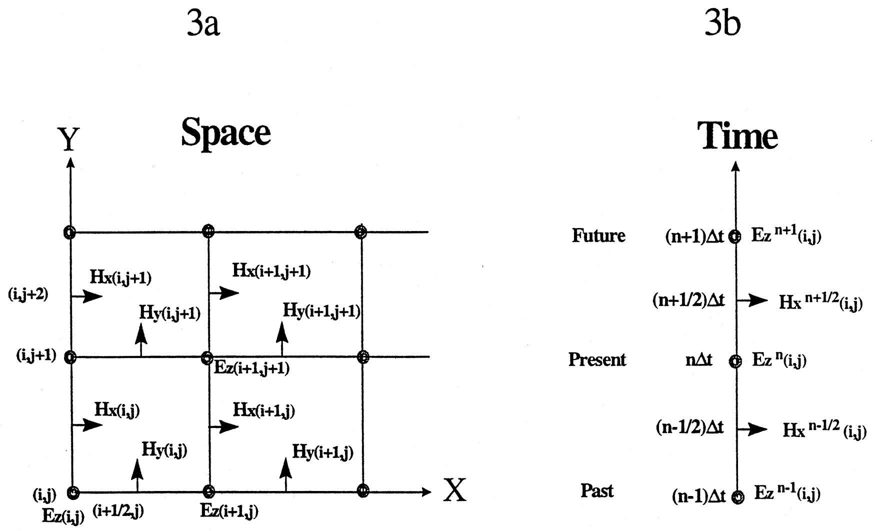

Fig. 3. Stencils used to discretize time and space within a microwave resonant cavity.

Figure 5 depicts the electric field calculated by the FDTD algorithm for an empty microwave resonant cavity. Cavity dimensions which satisfy conditions for resonance (at 2.45 GHz) are 0.0865×0.346 m. The structure shown corresponds to mode TE_{410} and is in excellent agreement with the results predicted by the analytical solution of Maxwell's equations. As expected, the incident plane located at $X = 0.043$ m does not create any discontinuity while the cavity is unloaded. Figure 6 shows how the electric field may be perturbed by the presence of a stationary slab of the beef tissue in the cavity. The dielectric tissue spans the full width of the cavity in the region between $X = 0.221$ and $X = 0.245$ m. This figure was generated by assuming uniform dielectric properties which correspond to those of beef tissue at -40°C. This situation corresponds to the transient case where the microwave field is suddenly turned on but due to thermal inertia no temperature change has yet occurred. It can be noticed that the E field is reduced by absorption in the cavity and within the tissue. More noteworthy is that the loaded cavity has been excited to a higher TE_{105} mode of resonance. This mode change significantly moves the region of maximum heating and illustrates the importance of simulation when heating with single mode cavities.

As time proceeds temperature increases which, in the case of biological tissues, increases energy absorption. Figure 7 shows the electric field within the cavity after 0.65 s. In all three cases the magnitude of the incident field was 150 000 V m^{-1}. It is seen that increased absorption has significantly altered the field. This variation in the E field illustrates the importance of using an iterative computational procedure which can account for temperature dependent dielectric properties. A discontinuity in the E field may also be seen at the location of the incident plane. This is partially an artifact that arises from the use of a finite mesh size and partially due to the impedance mismatch between the incident plane and the loaded cavity [10]. This mismatch is due to the absorption and scattering of the microwave field by the dielectric load in the cavity.

The temperature profile which corresponds to Fig. 7 is shown in Fig. 8. Here the beef tissue has been warmed for 0.65 s while exchanging heat with room temperature air on faces at $x = 0$ and $x = 0.0243$ m. The hottest region in the tissue corresponds to the maxima in the electric field. A temperature difference of nearly 30°C between the center and the edges of the tissue indicates that occurrence of thermal runaway is imminent. This illustrates a significant drawback to the use of microwaves in rewarming cryopreserved tissue which requires uniform heating with maximum temperature of only 40°C.

In Fig. 9 the temperature profile for a moving slab of dielectric material is shown after it has been heated 6.7 s which is the exact time interval for it to move across the cavity. This simulates a heating process where a con-

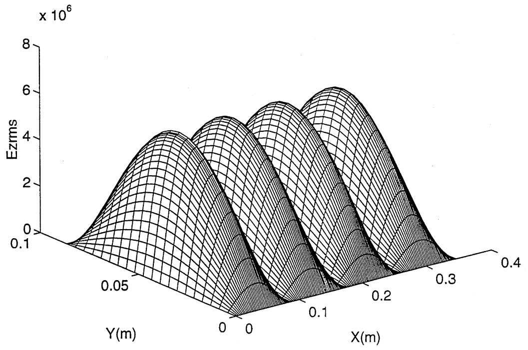

Fig. 5. The resonant electric field for an electric cavity.

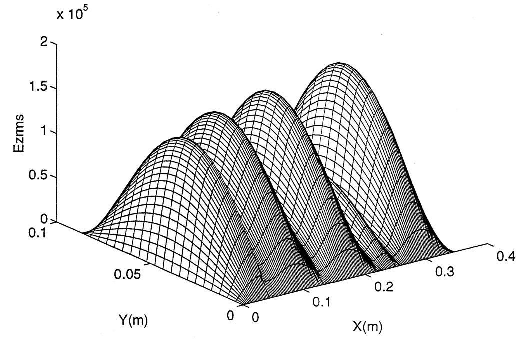

Fig. 6. The initial distribution of the dielectric is greatly distorted by the presence of a dielectric.

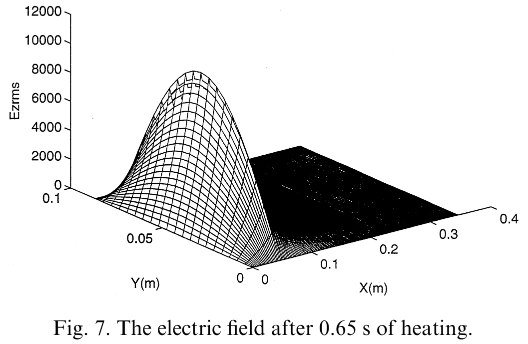

Fig. 7. The electric field after 0.65 s of heating.

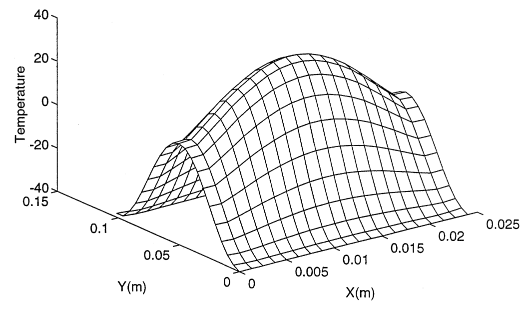

Fig. 8. The temperature distribution after 0.65 s of heating.

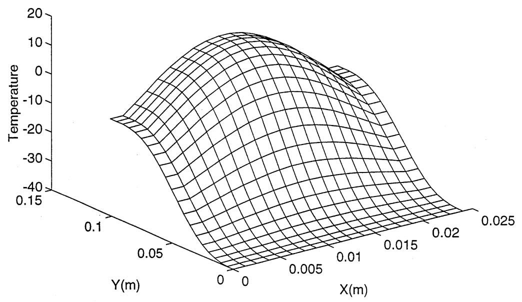

Fig. 9. The temperature profile for a dielectric which is moving through the cavity.

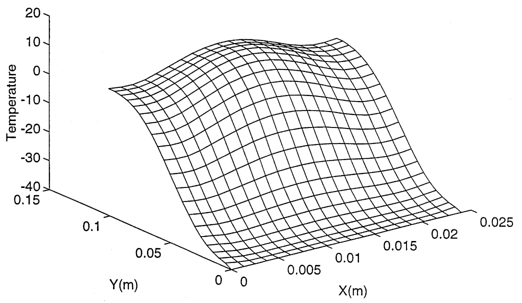

Fig. 10. The temperature profile produced by a continuous hybrid heating process.

tinuous stream of dielectric is moved through a microwave cavity while exchanging heat with air on faces $x = 0$ and $x = 0.0243$ m. With the tissue set into motion the advective term of the energy equation is brought into play and the temperature profile is no longer symmetric about the cavity centerline. Here the velocity is $V = 1.3$ cm s^{-1}, the heat transfer coefficient $h = 5$ W m^{-2} K^{-1}, and $T_\infty = 23°C$. With this configuration the peak temperature is about 12°C, and the maximum temperature variation is seen to be 19°C across the sample at the exit. The elevated temperatures near the center of the sample bring this region close to the threshold of thermal runaway yet the edges are still relatively cool. Figure 10 shows the results of increasing the convective heat flux. Here $T_\infty = 120°C$, $h = 40$ W m^{-2} K^{-1}, and all other parameters remain unchanged. Convective heat fluxes at $x = 0$ and $x = 0.0243$ m warm the sides of the tissue slab and significantly increase uniformity of the temperature profile. The peak temperature is about 5°C, and the largest temperature difference at the exit is about 2°C, and the overall warming rate is approximately 6°C s^{-1}, which significantly exceeds what would be possible by conduction alone.

With proper design a hybrid-heating scheme can offer multiple benefits. The convective heat flux augments microwave heating to produce higher warming rates or, for a given warming rate, the microwave power could be reduced, thereby diminishing the likelihood of the occurrence of thermal runaway. Since microwave heating is primarily a volumetric phenomenon the convective heat flux into the surface of the tissue can smooth out the temperature distribution. This can also act to suppress the occurrence of local hot spots and thermal runaway since the deposition of microwave energy is strongly coupled with temperature. An additional benefit is the relative ease with which the convective heat flux may be altered in order to maintain control of the warming process. It is generally simpler to vary T_∞ and h than it is to modulate the microwave power. Improved control of the warming process may also be obtained by utilizing a continuous heating process rather than batch heating. This numerical study has shown that by moving the tissue through the resonant cavity at an appropriate velocity the occurrence of thermal runaway may be avoided. The underlying reason is that the warmest (and most strongly absorbing) central region of the tissue may be continuously moved toward regions of lower electric field strength.

4. Conclusions

A numerical simulation of a continuous hybrid microwave heating process was developed and used to model an idealized process for producing rapid and uniform warming of cryopreserved tissue. FDTD methods were used to determine the electric field distribution in a loaded resonant cavity. Root-mean-square values of E field were then used as source terms in the energy equation. An iterative scheme was used to account for temperature dependence of dielectric properties. The multivariate and highly coupled nature of hybrid microwave heating makes numerical simulation a highly desirable tool for designing workable warming processes which would otherwise require expensive trial-and-error approaches.

References

[1] G.M. Fahy, Vitrification, in: Proceedings of Nato Advanced Study Institute on Biophysics of Organ Cryopreservation, Plenum Press, 1987, pp. 133–147.

[2] G.M. Fahy, Vitrification of multicellular systems and whole organs, Cryobiology 24 (1987) 581.

[3] T. Nei, Mechanism of hemolysis of erythrocytes by freezing at near-zero temperatures. I. Microscopic observation of hemolyzing erythrocytes during the freezing and thawing process. Cryobiology 4 (1967) 153–156.

[4] A.C. Metaxas, R.J. Meridith, Industrial Microwave Heating, Peter Peregrinus Ltd., London, 1983.

[5] Deepak, J.W. Evans, Calculation of temperatures in microwave-heated two dimensional ceramic bodies, Journal of American Ceramic Society 76 (8) (1993) 1915–1923.

[6] A.M. Karow, Electronic techniques for controlling thawing of major organs, Cryobiology 21 (1984) 403–406.
[7] E.C. Burdette, A.M. Karow Jr., Model for study of electromagnetic thawing, Cryobiology 15 (1978) 142–151.
[8] E.C. Burdette, S. Wiggins, R. Brown, A.M. Karow Jr., Microwave thawing of frozen kidneys: a theoretically based experimentally-effective design, Cryobiology 17 (1980) 393–402.
[9] National Research Council, Microwave Processing of Materials, National Academy Press, Washington, 1994.
[10] F. Liu, I. Turner, M. Bialowski, A finite difference time-domain simulation of power density distribution in a dielectric loaded microwave cavity, Journal of Microwave Power and Electromagnetic Energy 29 (3) (1994) 138–148.
[11] M. De Parc, Field and power-density calculations in closed microwave systems by three-dimensional finite differences, IEEE Proceedings, 1985, 132Pt H6, pp. 360–368.
[12] C.M. Furse, S.P. Mathur, O.P. Gandhi, Improvements to the finite difference time domain method for calculating the radar cross section of a perfectly conducting target, IEEE Trans. Microwave Theory Tech. 38 (1990) 919–927.
[13] D.M. Sheen, S.M. Ali, M.D. Abourzahra, Application of the three dimensional finite difference time domain method to the analysis of planar microstrip circuits, IEEE Trans. Microwave Theory Tech. 38 (1990) 849–857.
[14] A. Taflove, Application of the finite difference time domain method to sinusoidal steady state electromagnetic penetration problems, IEEE Trans. Electromagn. Commpat. 22 (1980) 191–202.
[15] A. Taflove, M.E. Brodwin, Numerical solutions of steady state electromagnetic scattering problems using the time dependent Maxwell's equations, IEEE Trans. Microwave Theory Tech. 23 (1975) 626–630.
[16] A. Taflove, K. Umashankar, Review of FD-TD modeling of electromagnetic wave scattering and radar cross section, IEEE Proceedings 77 (1989) 682–699.
[17] C. Wang, O. Gahndu, Numerical simulation of annular phased arrays for anatomically based model using FDTD method, IEEE Trans. Microwave Theory 37 (1989) 118–126.
[18] K.S. Yee, Numerical simulation of initial boundary value problems involving Maxwell's equations in isotropic media, IEEE Trans. on Antennas and Propagation 14 (1966) 302–307.
[19] X. Zhang, J. Fang, K.K. Mei, Y. Lui, Calculation of the dispersive characteristics of microstrips by the time domain finite difference method, IEEE Trans. Microwave Theory Tech. 36 (1988) 263–267.
[20] X. Zhang, K.K. Mei, Time domain finite difference approach to the calculation of the frequency dependent characteristics of microstrip discontinuities, IEEE Trans. Microwave Theory Tech. 36 (1988) 1775–1787.
[21] S.S. Zinanovic, K.S. Yee, A subgridding method for the time-domain finite difference method to solve Maxwell's equations, IEEE Trans. Microwave Theory Tech. 39 (1991) 471–479.
[22] J. Clemens, C. Saltiel, Numerical modeling of materials processing in microwave furnaces, International Journal of Heat and Mass Transfer 39 (8) (1996) 1665–1675.
[23] Q. Zhang, Parametric study of heating of a containerized liquid in a single-mode microwave cavity, MS thesis, Indiana University—Purdue University at Indianapolis, Indiana, 1998.
[24] K. Kunz, R. Leubbers, The Finite Difference Time Domain Method for Electromagnetics, CRC Press, Ann Arbor, 1993.
[25] S.V. Patankar, Numerical Heat Transfer and Fluid Flow, Hemisphere Publishing Corporation, New York, 1980.
[26] N.E. Bengtsson, P.O. Risman, Dielectric properties of foods at 3 GHz as determined by a cavity perturbation technique, Journal of Microwave Power 6 (2) (1971) 107–123.