A Parametric Study on Phase Change Heat Transfer Process during Cryosurgery of Lung Tumor

Sushil Kumar¹, Sazid Ali ², V. K. Katiyar³

¹ University Institute of Engineering and Technology, CSJM University India 208024
² Department of Mathematics, University of Rajasthan, Jaipur, India
³ Indian Institute of Technology Roorkee, 247667 (India)

Abstract

In present study finite difference method based on enthalpy formulation of Bio-heat equation has been used to study the heat transfer process involving phase change in lung tumor subjected to cryosurgery. The model was used to investigate the effect of cryoprobe radius, cryoprobe freezing temperature and heat generation due to blood perfusion and metabolism on the temperature profile, freezing front movement in tissue and tumor freezing time. Non-ideal property of biological tissues has been taken into account. It is found that (i) increase in cryoprobe diameter (ii) decrease in cryoprobe freezing temperature, lead to increase in minimum temperature, freezing rate, freezing area in tissue and decrease in tumor freezing time. Further decrease in minimum temperature, cooling rate, freezing area and increase in time to freeze tumor has been observed with the presence of heat source term compared to the case where heat source term was not included.

Keywords: Cryosurgery; Lung Tumor; Phase change; Enthalpy method.

1. Introduction

Cryosurgery is use of extremely low temperature with an instrument called as cryoprobe to damage all cancer cells while sparing adjacent healthy tissue [1]. This surgical technique is based on the cryotoxic effect of low temperature. The primary goal of cryosurgery is to maximize all mechanism that produces maximal destruction to undesired tissues while minimizing damage to surrounding healthy tissue [2, 3]. The factors affecting cell injury during cryosurgery include the coolest temperature in the tissue, the duration of frozen cycle, the rate of freezing front propagation, the thawing rate and the freezing/thawing cycles etc. [4-11]. The factors which affects necrosis such as the lowest temperature in the tissue or the rate of freezing front propagation depends on the biophysical parameter that are present in a given cryosurgical procedure, some of which may be selected and controlled by the surgeons. These parameters include the temperature and duration of freezing-thawing process, the shape and size of cryoprobe, the heat capacity, the thermal conductivity of the tissue, the rate of blood flow and rate of metabolism in the involved tissue [12]. Gage et al. [6] investigated the effect of varying freezing rate, duration of freezing and thawing rate on cell destruction in dog skin and suggested that the use of a probe as cold as possible, speeds freezing, expedites and increases the frozen volume of tissue. Blood perfusion and metabolic heat generation also have significant effect on heat transfer in tissues¹⁷, ¹⁸.
Neglecting of these terms can result up to 20% error in the result for the radius of the frozen zone [13]. The literature reveals that mathematical study on the effect of these parameters on phase change heat transfer process during cryosurgery is rare. Further lung cancer is the most common cancer worldwide accounting for 1.2 million new cases annually and is responsible for 17.8% of all cancer deaths. Due to large differences in thermal properties of the dense tumor tissue and low density of surrounding lung tissue, the physical phenomena associated with heat transfer during cryosurgery in lung are interested and unique.

In order to apply cryosurgery effectively, the knowledge of temperature transients in tumor and normal tissue as well as position of freezing interface are needed to say whether the tumor is damaged or not and to minimize the injury to healthy tissues. In biological tissues phase change occur over a wide range with upper phase change boundary at -1 °C and lower phase change boundary at -8 °C [14]. Heat generation due to metabolism and blood perfusion also take place. Thus a phase change phenomenon in biological tissues is quite different from ideal materials that have fixed freezing point. Analytical solution of these is extremely difficult, and even impossible if no substantial simplifications are introduced. Numerical solution using finite difference method is the most popular choice for these problems [12-21].

In the present paper a numerical study on the phase change heat transfer process during cryosurgery in lung tumor is presented. Penees bio-heat equation [22] is used to study the effect of cryoprobe radius, cryoprobe temperature, heat source term due to blood perfusion and metabolism on freezing process of tissue. Non-ideal property of tissue is used. Finite difference method using enthalpy approach is used to solve the mathematical model.

2 Mathematical model

Enthalpy formulation of bio-heat equation for phase change problem has been given as

\[ \rho \frac{\partial H}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( kr \frac{\partial T}{\partial r} \right) + \omega_b \rho_b c_b (T_b - T) + Q_m \]

where \( \rho \) is density of tissue; \( H \), enthalpy; \( k \), thermal conductivity; \( c_b \), specific heat of blood; \( \omega_b \), blood perfusion rate; \( T \), temperature; \( t \), time; \( r \), radial coordinate; \( T_b \), arterial blood temperature and \( Q_m \) is the metabolic heat generation in the tissue.

Following assumptions have been made to solve the bio-heat transfer model:

(i) Heat transfer is purely by conduction [23].
(ii) Non-ideal property of tissues is used with liquidus and solidus temperature as -1°C and -8 °C respectively [14].
(iii) Thermo-physical properties are different in frozen and unfrozen region.
(iv) Thermal properties of tumor and lung tissues are different [2,14,16-18].

3 Numerical solution and results

Finite difference explicit scheme [23] is used to solve the above mathematical model with appropriate boundary and initial conditions. Once the new temperature field is
obtained from enthalpies the process repeats. Isotherms at -1°C and -8°C give the position of upper and lower phase change interfaces $s(t)$ respectively.

To study the effect of cryoprobe radius on cell destruction, cryoprobe of 3, 5 and 8 mm in diameter [3] with freezing temperature -196°C are simulated to freeze the tissue for 900 sec. An increase in minimum temperature in tissue is observed with increase in diameter. It indicate that the larger the diameter of cryoprobe, the lower the freezing temperature in tissue. Freezing interfaces move fast and produced larger freezing region for 8 mm cryoprobe compared to 3 and 5 mm cryoprobe. Simulation results also show that 8 mm cryoprobe produces lowest temperature and maximum freezing area in tissue. The reason is that cryoprobe of larger diameter provides greater physical area between its surface and tissue, hence larger heat is removed by cryoprobe producing better freezing potential and freezing range.

Cryoprobe with 3 mm diameter with freezing temperature $T_s = -196$°C, -150°C and -120°C is used to study the effect of cryoprobe temperature on temperature profile and freezing front position in tissue. Freezing time is taken as 2000 sec. It is also observed that the cryoprobe with $T_s = -196$°C produces 39.47% and 15.22% increase in freezing region compared to $T_s = -120$°C and $T_s = -150$°C. Also cryoprobe with $T_s = -150$°C and -196°C take 570.38 sec and 919.4 sec less time respectively compared to $T_s = -120$°C to freeze the tumor. Reason is that cryoprobe with lowest temperature removes maximum heat from tissue thus results in lowest temperature, fast cooling and largest freezing extent.

To study the effect of heat source term $q = \omega_b \rho_b c_b (T_b - T) + Q_m$, cryoprobe of 3 mm diameter with $T_c = -196$°C is used to freeze the tissue for 900 sec. Minimum temperature is observed in tissue for the case without heat source term compared to the case with heat source term. The presence of heat source term increases the difficulty of freezing the targeted tissue, the freezing rate and the minimum temperature in tissue. Thus metabolic heat generation and blood perfusion have a significant effect on temperature profile, freezing interface propagation in tissue.

4 Conclusion

The effect of cryoprobe diameter, cryoprobe temperature and heat generation due to metabolism and blood perfusion on phase change heat transfer process during cryosurgery in lung tumor has been analyzed numerically. Results show that (i) increase in cryoprobe diameter (ii) decrease in cryoprobe freezing temperature, lead to increase in minimum temperature, freezing rate, freezing area in tissue and decrease in tumor freezing time. Further decrease in minimum temperature, cooling rate, freezing area and increase in time to freeze tumor has been observed with the presence of heat source term compared to the case where heat source term was not included. Results obtained are expected to be helpful in pre-selecting the parameters to optimize the freezing protocols.

References

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