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INVESTIGATION ON THE COMPLEX 3-D HEAT TRANSFER PROBLEMS FOR THE COMBINED CRYOSURGERY AND HYPERTHERMIA THERAPY WITH MULTIPLE FREEZE-HEATING CYCLES

Zhong-Shan Deng [1], Jing Liu [1, 2]

[1] Technical Institute of Physics and Chemistry, Chinese Academy of Sciences,
Beijing 100080, P. R. China

[2] Department of Biomedical Engineering, Tsinghua University,
Beijing 100084, P. R. China

INTRODUCTION

Since the beginnings of modern cryosurgery, the need for repetitive freezing in the cryosurgical treatment of cancer has been recognized. Many investigations have suggested that multiple freeze/thaw cycles can result in significantly strong damage to the tumor and better outcome than a single cycle [1, 2]. The repeated cycle would produce faster and more extensive tissue cooling, so that the volume of frozen tissue can be enlarged and the border of certain tissue destruction will be moved closer to the outer limit of the frozen volume [3]. For this reason, repetition of the freeze-thaw cycle is important for the tumor treatment.

Recently, a new tumor ablation modality based on the freezing immediately followed by a strong heating had been proved to be more effective and flexible than the conventional cryosurgery [4, 5]. Similar to freeze/thaw cycle of cryosurgery, the freezing/heating process during the combined cryosurgery and hyperthermia can be termed as freeze/heat cycle. Because the combined cryosurgery and hyperthermia system is a new modality for tumor treatment, the freeze/heat behaviors of biological tissue subject to it have received few attentions up to now, and the complex three dimensional (3-D) heat transfer characteristics involved in multiple freeze/heat cycles remain unclear up to now.

With the increasing applications of such new conceptual combined system, it becomes apparent (same as cryosurgery) that without good knowledge of temperature distributions within tumors and the surrounding normal tissues during multiple freeze/heat cycles, it is difficult to tell whether the target tissue has been frozen/burned adequately and irreversibly damaged. And in some applications, it is also difficult to control and adjust the fixed probe configuration to produce an expected irregularly shaped lesion, which is to maximize the tumor killing effect while minimizing thermal injury on healthy tissues. In addition, especially for multiple probe application, such problem appears more complex, because during the alternate procedure of freeze/heat, multiple probes will produce more phase change interfaces (as shown in Figure 1).

Similar to cryosurgery, an optimum technique of the combined cryosurgery and hyperthermia will also require a thorough understanding of the freeze/heat cycle and its components. For this purpose, the complex 3-D bioheat transfer problems involved in multiple freeze/heat cycles during the combined cryosurgery and hyperthermia was investigated in this study.

METHODS

Using the effective heat capacity method, the energy equation simultaneously describing for frozen, partially frozen and unfrozen tissues during freezing/heating process can be written as:

$$\tilde{C}\frac{\partial T(\mathbf{X},t)}{\partial t} = \nabla\cdot\tilde{k}\nabla T(\mathbf{X},t) - \tilde{\omega}_b C_b T(\mathbf{X},t) + \tilde{Q}_m + \tilde{\omega}_b C_b T_a\,,\ \ \mathbf{X}\in\Omega \qquad (1)$$

where $\tilde{C}$ is the effective heat capacity; $\tilde{k}$ is the effective thermal conductivity; $\tilde{Q}_m$ is the effective metabolic heat generation; and $\tilde{\omega}_b$ is the effective blood perfusion.

The numerical algorithm and computer code used in this study is modified from that developed in our previous work [6].The description and derivation of the algorithm is omitted here for brevity. Readers are referred there for more details.

RESULTS AND DISCUSSION

Figures 2-4 shows part of results, in which 3 probes with different insertion depths are applied, and 3 freeze/heat cycles are conducted (each freeze/heat cycle includes 9 min freezing and succedent 3 min heating). The results suggest that the combined cryosurgery and hyperthermia system has strong freezing and heating capability, and that it may improve the treatment effect by providing double chances to possibly kill the target tissues. It is also indicated that employing multiple freeze-heat cycles can create a wider lesion area, which is favorable for the treatment of large tumors. In addition, due to the strong heating performance of the combined system, the probes may be easily re-positioned between each cycle to produce more complexly-shaped ablation region when multiple freeze-heat cycles are used. This potential feature has important clinical implications for the practical use of such system in the treatment of tumor.

Further results (including some experimental measurements) and detailed discussion will be presented at the conference.

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REFERENCES

[1] Pisters, L. L., von Eschenbach, A. C., Scott, S. M., Swanson, D. A., Dinney, C. P., Pettaway, C. A. and Babaian, R. J., 1997, “The efficacy and complications of salvage cryotherapy of the prostate,” Journal of Urology, **157**, pp. 921-925.

[2] Woolley, M. L., Schulsinger, D. A., Durand, D. B., Zeltser, I. S. and Waltzer, W. C., 2002, “Effect of freezing parameters (freeze cycle and thaw process) on tissue destruction following renal cryoablation,” Journal of Endourology, **16**, pp. 519-522.

[3] Baust, J. G. and Gage, A. A., 2005, “The molecular basis of cryosurgery,” BJU International, 95, pp.1187-1191.

[4] Liu, J., Zhou, Y. X., Yu, T. H., Gui, L., Deng, Z. S. and Lv, Y. G., 2004, “Minimally invasive system capable of performing both cryosurgery and hyperthermia treatment,” Minimally Invasive Therapy and Allied Technologies, **13**, pp. 47-57.

[5] Liu, J., Zhou, Y. X., Yu, T. H., Gui, L., Deng, Z. S. and Lv, Y. G., 2003, “New cryoprobe system with powerful heating features and its performance tests on biomaterials,” ASME International Mechanical Engineering Congress and RD&D Expo, Washington, D.C., Nov.14-23, 2003.

[6] Deng, Z. S. and Liu, J., 2004, “Numerical simulation on 3-D freezing and heating problems for the combined cryosurgery and hyperthermia therapy,” Numerical Heat Transfer, Part A: Applications, **46**, pp. 587-611.

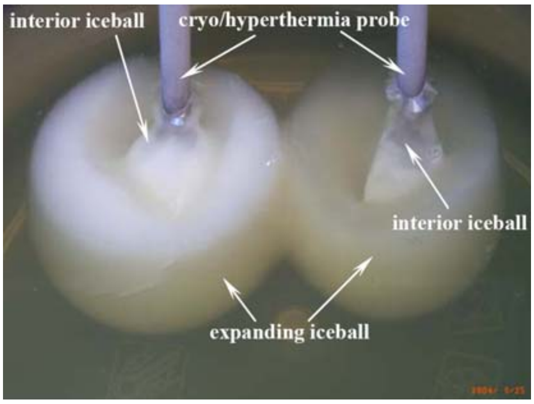

Figure 1. The iceballs produced in phantom gel by 2 probes during freeze/heat cycle using combined cryosurgery and hyperthermia system (made in our lab)

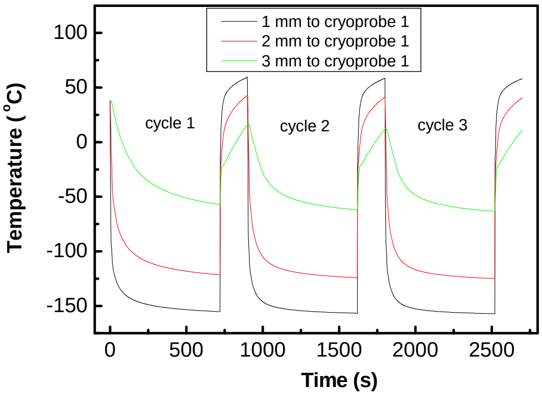

Figure 2. Transient temperature responses of tissues at three given positions during 3 freeze/heat cycles

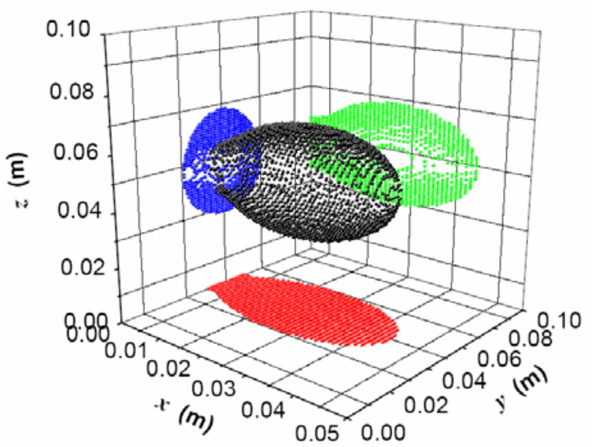

Figure 3. Iceball produced at the third cycle (t=2520 s)

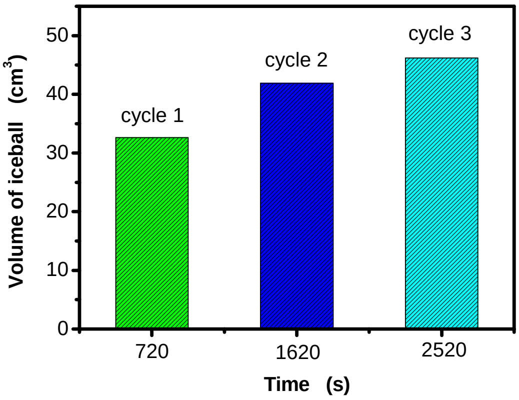

Figure 4. The volume of iceball produced at the end of each cycle