THERMAL ENGINEERING APPROACH TO CRYOSURGERY

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論　文　内　容　の　要　旨

Cryosurgery is a minimally invasive surgical technique that uses cryoprobes or cryoneedles to freeze and destroy tumors or undesirable tissues. Recently, it is operated with non-invasive monitoring technologies such as MRI and ultrasonography to distinguish frozen regions in tissues and organs. However, the most important issue during cryosurgery is to expose all cancer cells to lower than their lethal temperature, normally −20 or −40°C, indicating that only producing an ice ball at a tumor is not enough for eradication of the complete tumor. However, excess freezing could easily induce side effects. Hence, determining the size of the ice ball is a key issue in cryosurgery. The present dissertation research therefore dedicates to provide important information and guidelines to medical doctors for operation of cryosurgery from thermal engineering points of view by conducting experiments and simulations.

In Chapter 1, the background of the cryosurgery was presented. The history and the origin of the cryosurgery were discussed. The state-of-the-art cryosurgery that uses cryoprobes cooled by the Joule-Thomson (J-T) effect of argon gas was also presented. Then, several engineering research work about cryosurgery experiments and numerical models were provided, followed by the introduction of predicting temperature distribution in tissues with the bioheat equation. Finally, the chapter ended by summarizing the motivations and objectives of the dissertation.

Chapter 2 presents experimental validation of cooling performance of the commercially used J-T cryoprobe, CryoHit™ Needle, which is not available in the open literature in spite of its importance for operation of cryosurgery. The temperature at the probe surface and the radial temperature distribution were examined from an in-vitro experiment using a tissue phantom at three different pressures of supplied argon gas. A simulation based on an apparent heat capacity model was also validated by a comparison with the experimental results. The experiments revealed that the freezing with a single probe could only treat tumors smaller than 10 mm. Finally, a guideline for determining a safety margin of an ice periphery was proposed for a given size of tumor.

In Chapter 3, the similar experiments were conducted using two parallel cryoprobes for treating larger tumors. Two cryoprobes were placed in the tissue phantom at different center-to-center distance, 10 or 20 mm. The experiment revealed that using two probes had a combined effect to make the probe temperature lower when they were used at close distance. However, the temperature at the center of an ice ball between the cryoprobes was considerably higher than the probe surface particularly at 20-mm distance, which might induce insufficient damage of cancer cells at the middle of tumor. The result

therefore indicated that we must use two cryoprobes within 10-mm distance.

Chapter 4 examined the feasibility of using apparent thermophysical properties for estimation of temperature distribution in tissues. The estimation is important for some medical therapies, and has been done using Pennes bioheat equation that includes a term of blood perfusion. However, unfortunately, the accurate value of blood perfusion rate is often unavailable for human tissues. This chapter therefore aimed to examine if we can use the apparent thermophysical properties with the normal heat conduction equation to consider the effect of blood flow in tissues. A comparison between the results of solving the bioheat equation and the normal heat conduction equation indicated that either apparent thermal conductivity or the apparent heat capacity does not work for the purpose. However, it was demonstrated that the size of ice ball during freezing process was successfully predicted by using the apparent thermal conductivity in the heat conduction equation instead of solving the bioheat equation.

Chapter 5 provides experiments associated with the potential solution to the problems in the lung cryosurgery. The lung is filled with the air instead of physiological liquids that normally occupies tissues and organs. Since this may obstruct the growth of ice ball, one of the solutions is to inject a liquid to enhance freezing. However, the physiological saline, which is the most popular solution used for medical purposes, easily diffuses out after injection in the lung. The experiment in this chapter is therefore designed to examine the feasibility of using bio-sodium hyaluronate solution or the lipiodol as an adjuvant because they have high biocompatibility and higher viscosity. The result indicated that the ice ball produced in the 1 % sodium hyaliuronate solution is almost the same as that in the tissue phantom obtained in Chapter 2. This demonstrates that we can neglect the effect of hyaluronic acid in terms of the size of ice ball and the temperature distribution. The guideline for the safety margin of the ice periphery proposed in Chapter 2 is therefore useful even in the case of injecting bio-sodium hyaliuronate solution instead of a physiological saline to avoid quick diffusion in a tissue. However, since the ice ball produced in lipiodol was considerably smaller, it is not appropriate for the adjuvant.

Chapter 6 provides the main conclusions and findings in the present study, and the potential future work as well.