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Development of Reformative Surgery Method using Partial Freezing for the Liver

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Abstract: To minimize surgical stresses including blood loss and operation time to the patients during hepatic resection, we studied a feasibility of a combination of partial liver freezing technique and shape-memory alloy, which also enables a free-designed resection curve. In this surgical procedure, the region surrounding a tumor in the liver is frozen to excise and prevent hemorrhage. The liver was frozen by a Peltier module. The effects of cooling rate and freezing temperature on the excision force arisen between a scalpel and the liver are carried out experimentally as a basic research for partial freezing surgical procedures. A porcine liver was used as a liver sample. The physical properties were estimated by using the finite element method based on the heat transfer characteristics of the liver.

Isolation of the liver was conducted using a scalpel attached to the end-effector of a three degree freedom robot. In the experiments, the minimum excision force was obtained at a temperature between 272 K and 275 K; therefore, it is preferable that the liver be excised within this temperature range. Lowering of the cooling rate decreases the excision force even if the temperature of the liver remains unchanged. The lower the temperature of the liver is, the larger the increment rate of excision force is with regard to the cooling rate.

Key Words: Liver, Cancer, Surgical Operations, Partial Freezing Method, Heat Transfer Characteristics, Excision Resistance

1. INTRODUCTION

Surgical operations on the liver to remove tumors require excision of the tissue around the cancer cells. At present, during surgery, the numerous blood vessels found inside the liver, both large and small, are individually sutured or closed by coagulation. As a result, operations usually take from 4 to 8 hours, making them physically taxing for both the patient and the surgeons. As for the operation, usually the amount of the hemorrhage, the cancer retention and the passage after the operation are evaluated rather than the operation time. To shorten the operative time, however, it is most important that the adequate excision line simulated before the operation should be able to be secured and the hemorrhage should be able to be controlled. There is an urgent need to lighten this burden by developing innovative surgical methods that shorten the excision surgery time. As shown in Fig. 1 (a), the conventional liver cancer surgery requires a

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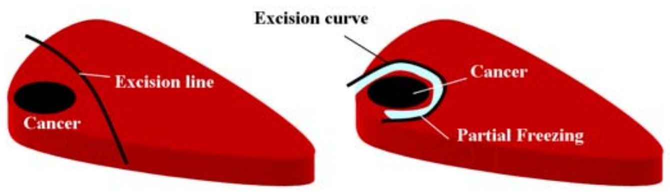
considerable volume of liver tissue to be excised, since the excision line is virtually straight. Furthermore, the range of excision is usually decided based on the Couinaud classification of liver segments [1]. Medical professionals have emphasized a need for the development of an optimized method that enables the excision of the tumor only, as shown in Fig. 1 (b). Unfortunately, it is difficult to excise the liver along the excision line under normal conditions, since the liver is soft and mobile.



(a) Past excision line. (b) The optimal excision curve.

Figure 1. Excision line of the liver cancer.

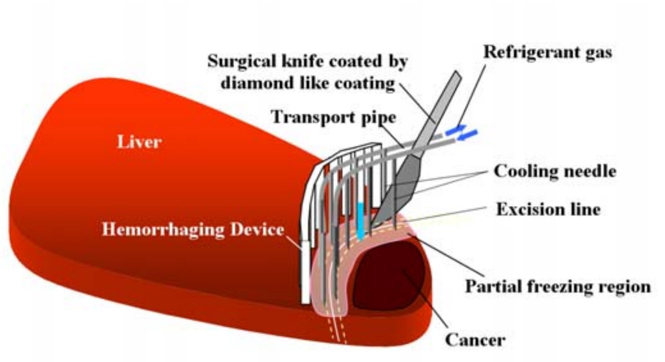


Figure 2. Schematic illustration of new surgery technique for the liver cancer.

To enable the excision of tumor within an arbitrarily chosen line or curve, our research group proposes a feasibility of a combination of partial liver freezing technique and shape-memory alloy, which enables a free-designed resection curve as shown in Fig. 2.

In this study, we first conducted a cooling test of the liver using a cooling needle to evaluate the liver's physical properties and to identify the characteristics of cooling of liver. Then, we performed a liver excision experiment using a robot system to investigate the effects of cooling rate on the excision resistance.

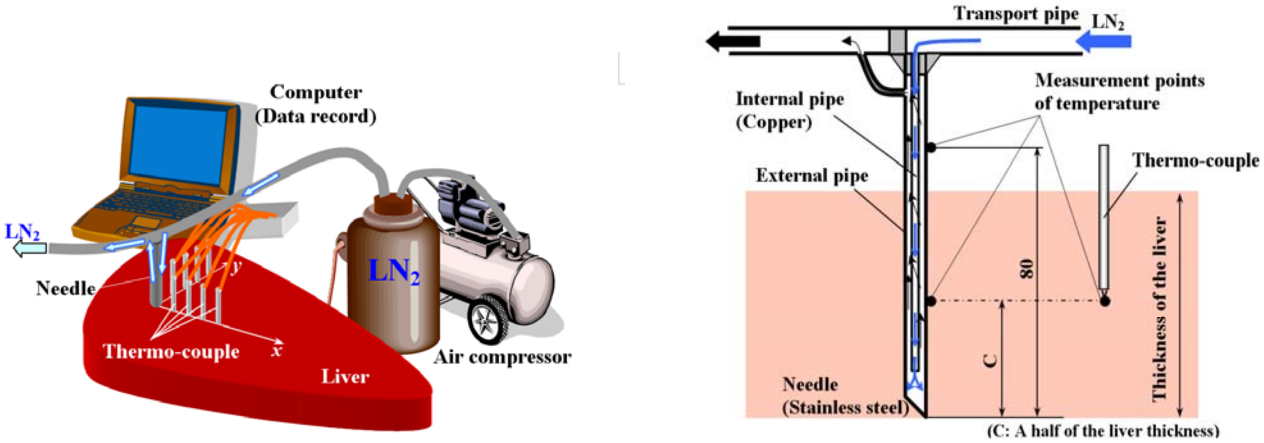
2. LIVER HEAT TRANSFER CHARACTERISTICS AND ANALYSIS OF THE MODEL

2.1 Heat transfer test

Since many liver cancer patients have cirrhosis as a complication, arterial blooding flow entering the liver may only be stopped for 5 minutes maximum during surgery. Surgeons must therefore cool the area of the liver around the excision line to a partial freezing state within 5 minutes. The partial freezing state is determined by the following excision resistance test.

The liver used in the test was a fresh porcine liver, which keeps fresh at 278 K or less and is not perfused during the following experiments. To cool the liver, we adopted a cooling system using liquid nitrogen. Figure 3(a) shows a schematic illustration of this system. The flow rate of the liquid nitrogen is set by adjusting the volume of air pumped from the compressor. The liquid nitrogen is led inside a cooling needle via a double-structured copper pipe whose inner diameter is 2 mm as shown in Fig. 3 (b).

A cooling needle was inserted deep into the liver and the temperature was measured at two points along the needle. At the same time, thermocouples inserted at depth of a half-thickness of the liver and at 5 mm



(a) Cooling system.

(b) Structure of cooling needle. It has a coaxial design: the internal pipe leads the liquid nitrogen to the tip of the needle. As it flows past the outer pipe, the nitrogen, now in gaseous form, cools it before exiting to the atmosphere.

Figure 3. Experimental system for heat transfer test of the liver.

intervals from the needle up to 20 mm away from the needle detected the cooling time and the temperature distribution. Due to the assumed anisotropic properties of liver tissue, measurements were taken in two directions, x and y. We did not consider the arrangement of blood vessels in this study.

2.2 Heat transfer characteristics of liver

Figure 4 shows the variation of the temperature versus time from the beginning of cooling. The solid and dashed lines show the temperature at each position on the cooling needle surface. The initial temperature of the liver is 282 K. Areas with up to a 15 mm radius from the cooling needle seemed to have frozen within 5 minutes. By using a number of these cooling needles side by side, it should be possible to reduce cooling time and to freeze a larger volume. In general, liver is an anisotropic material with heat transfer characteristics that depend on the arrangement of the blood vessels and the orientation of blood flow. Even without blood flow the heat transfer characteristics remain anisotropic which can be seen in Fig.4. It is reasonable to assume that the heat transfer characteristics are anisotropic perpendicular to x-y plain. However, since the disparity in heat flow characteristics are small (within 7 % or less even at x = y = 5 mm), we shall assume an isotropic model in the discussion of the following experiments.

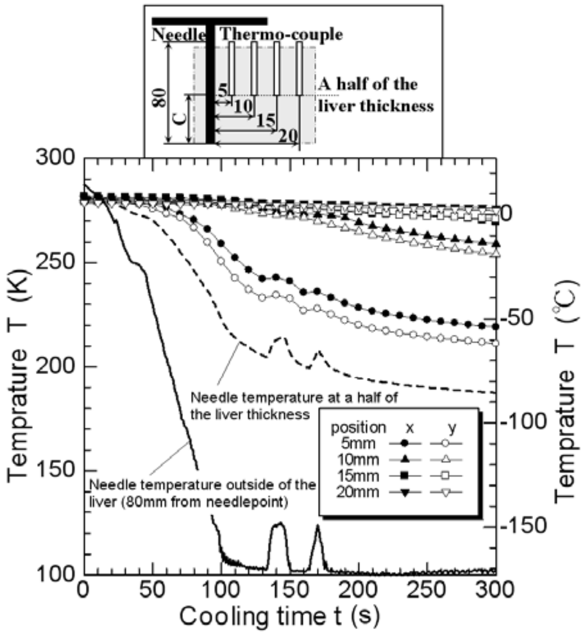


Figure 4. Relationship between temperature and cooling time of the liver.

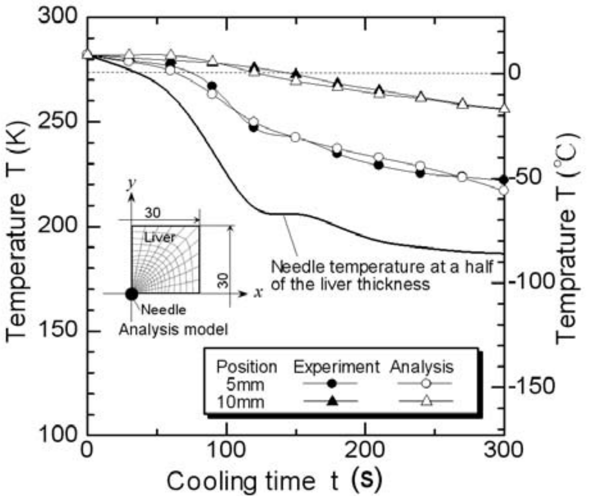


Figure 5. Analysis model and comparison of experimental and analysis data.

Heat transfer of the liver is analyzed by the finite element method, using the commercial finite elements code (MARC), with respect to two-dimensional unsteady-states conduction because the temperature distributions on the 2D plane were measured in the experiment. Furthermore, assuming that the lengthening joint of the needle was ideally cooled, conduction in the sample height can be neglected. Given the symmetry of the problem calculation of the model was confined to one-quarter the cooling area of 30×30 mm^2 (see Fig. 5). The cooling needle of 3 mm dia. is located at the center of the plane. The total number of elements and nodes are 190 and 220 respectively. Four node isoparametric bilinear quadrilateral elements have been used for this model. The mass density of the liver model was 1050 kg/m^3, which was measured in experiment. The boundary conditions were taken as the initial conditions. The liver was initially at 282 K. The temperature of the cooling needle was kept at 75 K. The thermal energy loss between the needle and the liver was neglected. By making a comparison with the temperature obtained by experimental measurement, we attempted to estimate numerically the physical properties of the liver. In experimental data shown in Fig.4, the temperature plateau induced by the latent heat of water can not be confirmed clearly. Although the latent heat of water is taken into consideration in this FEM inverse analysis, we consider that the latent heat does not have large effect on the heat transfer under a rapid cooling rate by using liquid nitrogen. Extracellular liquid around the liver tissue seem to have frozen by a rapid cooling and freezing completely did not happen inside the tissue. Figure 5 shows the comparison made between the numerical results and the measurement values when the distance from the cooling needle (x) was 5 mm and 10 mm. The solid lines in Fig. 5 show the temperature distribution of the cooling needle given under the initial conditions. If the values shown in Table 1 are used in the numerical analysis, the experimentally measured values are close to the numerical values when x is equal to 5 mm. These values around at 280 K are almost equal to those of Ref. [2].

Table 1 Thermal properties of the liver at non frozen region analyzed by FEM.

Thermal conductivity [W/(m·K)]	**Specific heat [J/(kg·K)]**	**Mass density [kg/m^3]**	**Thermal diffusivity [m^2/s]**
0.52	**3000**	**1050**	**0.15×10^{-6}**

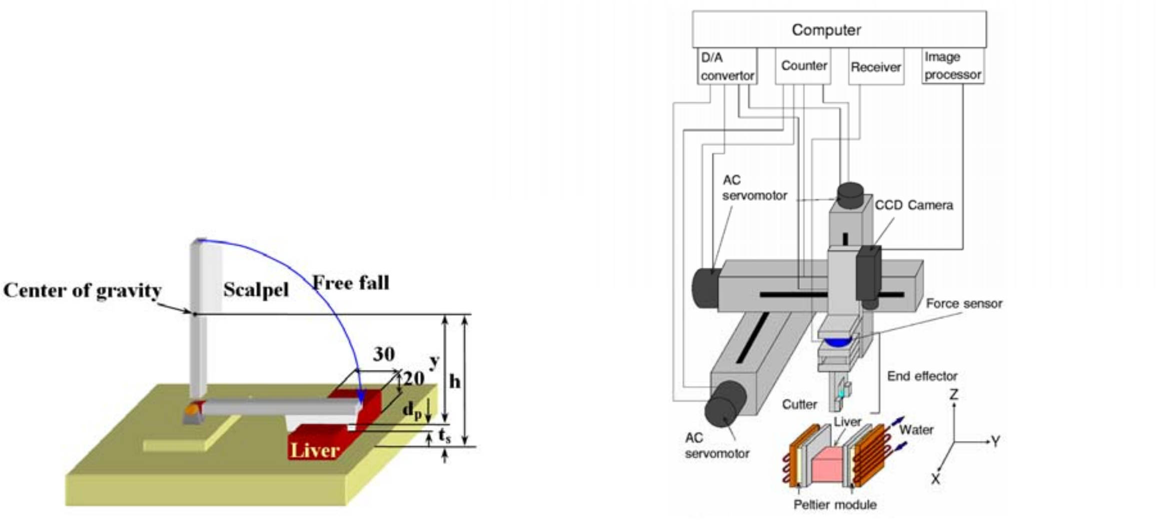
3. INFLUENCES OF COOLING PROPERTIES ON EXCISION RESISTANCE

3.1 Temperature of the liver and excision resistance

Figure 6(a) shows a schematic illustration of the experimental equipment we prepared to test the force of excision resistance under cooling conditions. The scalpel attached to the arm was allowed to drop freely to cut the liver samples to the hexahedron shaped volumes of 30×20×100mm3. After measuring the depth and length of the cut from the scalpel, we evaluated the excision resistance force F (N) as the following:

$$F = Mg\left(\frac{y}{d_p} + 1\right) \tag{1}$$

so that y = h - ts, where h is the height (m) from the center of gravity of the rod to the liver, ts is the height



(a) Excision force testing method (b)Excision test using robot system.

Figure 6. Excision force tests of the liver at several freezing conditions.

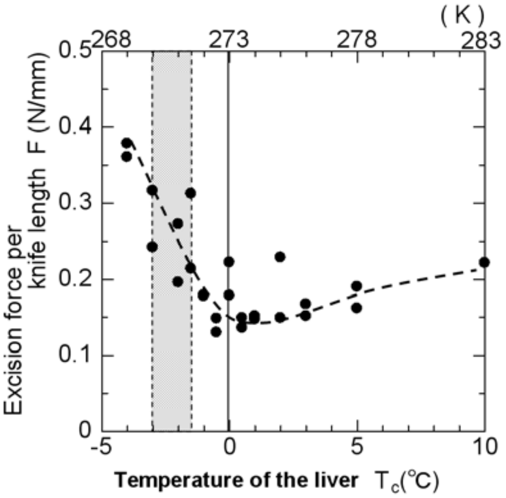


Figure 7. Relationship between excision force and temperature of the liver.

(m) of the liver being tested, M the mass (kg) of the rod and the scalpel, g is the acceleration (m/s2) due to gravity, dp is the depth (m) of the cut. The liver was set to the designated temperature by being placed inside a temperature-controlled tank until it had equilibrated at the desired temperature. We then calculated the excision resistance force as a function of different liver temperatures. This experiment was executed twice at each temperature.

Figure 7 shows the relationship between the temperature of the cooled liver and excision resistance. The vertical axis shows the excision resistance per scalpel length. It can be seen that a temperature range of 272 to 275 K provides minimum resistance force. At temperatures above 275K, the liver becomes elastic and rubbery, and resists penetration of the scalpel. As a result, excision resistance increases. On the other hand, if the temperature drops below 273K, the fine ice crystals contained inside the liver bind and solidify, with excision resistance increasing proportionally. Therefore, the temperature range of 272 to 275K is suited for conducting efficient liver excision, because there are partial freezing in the state of blood and liver tissue.

3.2 Excision resistance test using a robot

We then conducted a liver excision experiment using a robot system, with the temperature of the liver between 270K and 271.5K. Figure 6(b) shows the three degrees of freedom robot which we used as the manipulator. For the coordinate system, we used X, Y, and Z, and equipped axis Z of the manipulator with a scalpel (end effector) that had been fixed firmly in place by an aluminum plate. We used a CCD camera to load the images into the computer, confirmed the central point of the liver, then cut into it. The excision resistance applied to the scalpel during this excision process was recorded by means of a six-axle force sensor that had been attached to the end effector. The information data on the forces experienced by the end effector during the excision process were loaded into the computer through a receiver board. The liver was cooled from both sides using a two-sheet Peltier module, which has the following specifications: size of 40×40×4mm3, maximum current of 8.5A, maximum voltage of 16.4V and maximum dissipation of 81.5W. The excision was begun as soon as the temperature, indicated by the thermocouples embedded near the excision line, reached the designated level. The liver was excised with the scalpel vertically applied from above at a rate of 10 mm/s. The positions of the temperature measurement were at both ends on excision

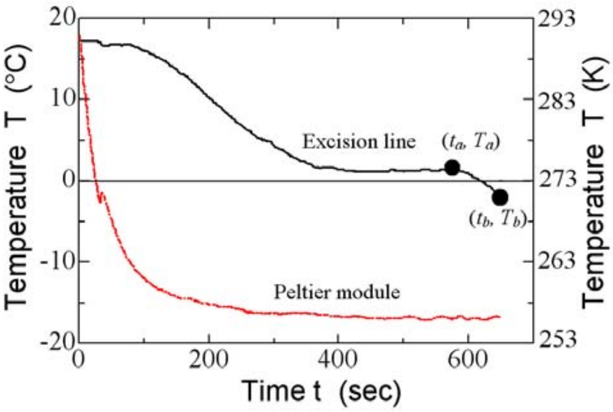


Figure 8. Cooling rate of the liver by a Peltier module.

line. The cooling rate was calculated from the temperature drop on the excision line. The range of the cooling rate was set in a few Kelvin per minute, a rate that is thought to cause minimum biological damage. [3]

Figure 8 shows the relationship between the cooling time and the temperature on the excision line, when the liver had been cooled. As shown in the figure, a temperature plateau is reached while cooling the liver at around 274K, after which the temperature begins to drop again. The temperature plateau, which was a result from the release of latent heat and changed thermal properties of liver due to freezing, appeared clearly. Peltier module is inferior to the cooling velocity compared with the cooling method of the previous description. In this excision resistance test using a robot, therefore, the cooling rates on the excision line were defined as the slope between point (ta, Ta) at which the temperature begins to drop again after reaching a state of equilibrium, and point (tb, Tb) at which the excision temperature has been reached. After the experiment, we calculated the rate of cooling using the following equation.

$$V_f = \frac{T_b - T_a}{t_b - t_a} \tag{2}$$

Figure 9 shows the results of our experiments on rate of cooling and excision resistance at different excision temperatures (Te). The straight lines in the figure indicate the least-squares method. It is clear that excision resistance data is scattered at the same cooling rate. Excision resistance is greatly affected by the

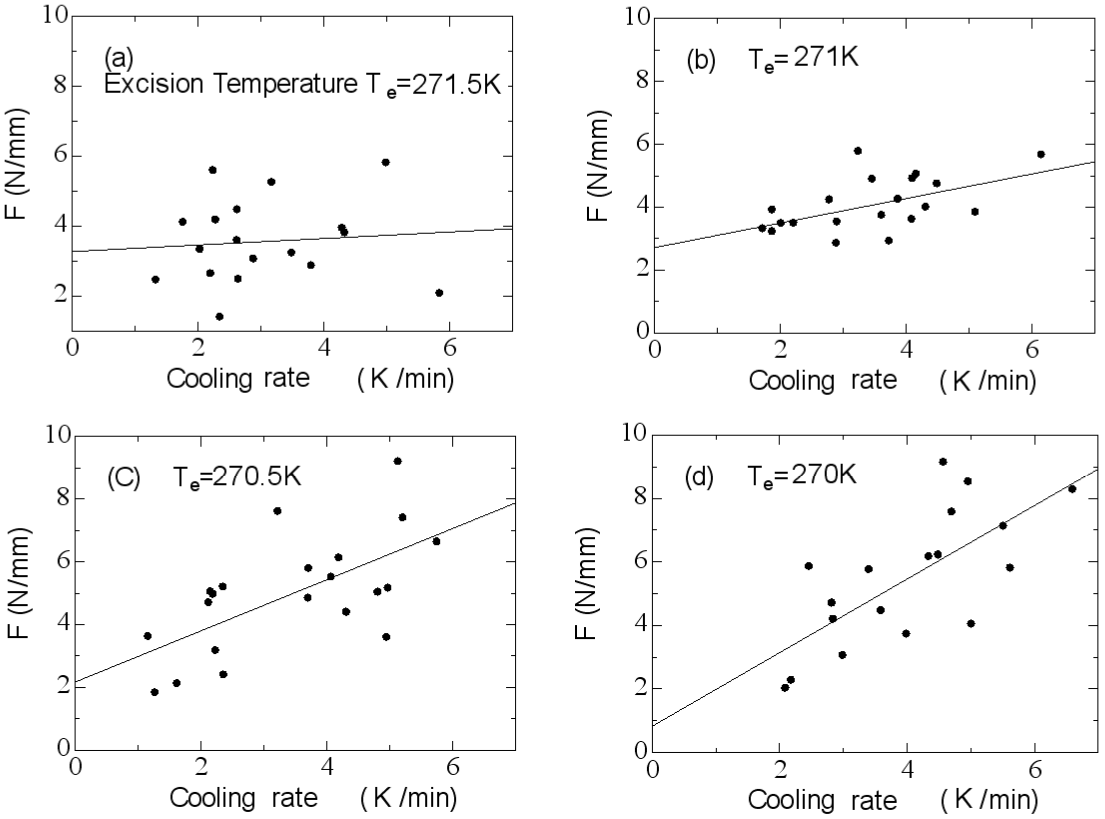


Figure 9. Relationship between excision resistance and cooling rate at each temperature.
(a) Excision temperature T_e= 271.5, (b) T_e= 271, (c) T_e= 270.5 and (d) T_e= 270K

liver's frozen status. More studies are needed to closely monitor the liver cells' status when the state of freezing is increased. Reducing the rate of cooling, even to the same eventual excision temperature, can reduce the force of excision resistance. The lower the excision temperature, the greater the effect of rate of cooling on the excision resistance is. Therefore, the excision should conducted at temperatures above 271K.

4. CONCLUSIONS

We carried out experiments on the liver to study its cooling characteristics and conducted excision tests. We obtained the following conclusions.

1. The reference value of the thermal conductivity and the thermal diffusivity of the liver can be estimated by finite element analysis based on the data of the heat transmission test.
2. The temperature range of the minimum excision resistance is between 272K and 275K.
3. Since excision resistance is greatly affected by the rate at which the liver is cooled, it is important to monitor closely the liver cells' status using the temperature recognition by image processing when frozen.
4. Since the properties of the liver vary depending on the cell tissues, moisture content, perfusion of biological tissues, capillary effect from the viewpoint of thermo- and fluid dynamics, it will be necessary to investigate the characteristics of the liver itself more closely.

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