Temperature Prediction Model for Advanced Renal Function Preservation in Partial Nephrectomy

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Abstract. The standard procedure for small renal cell carcinoma is a partial nephrectomy. In this procedure, renal blood flow is interrupted during tumor resection to control bleeding. It is known that cooling the kidney (cold ischemia) during this procedure reduces postoperative deterioration of renal function. The optimal deep renal temperature for cold ischemia is about 20 °C. However, the only method for measuring the deep renal temperature is an invasive needle puncture with a thermocouple. In the past, we have used thermal imaging cameras to simulate intraoperative tissue heat conduction and quantify heat diffusion in biological tissues. We will apply this experience to establish a simple, noninvasive method for measuring deep kidney temperature by creating a formula model to predict deep kidney temperature from the kidney surface temperature using a thermal imaging camera. In this study, we develop a temperature prediction model that can predict the deep kidney temperature from the surface temperature of the kidney measured with a thermal imaging camera. Using pig kidneys, we measure the temperature change when the kidneys are cooled. And we estimate the thermal diffusivity of the kidneys by comparing the actual temperature change data with the results of 3D unsteady heat conduction simulation. At this point, we have already estimated the thermal diffusivity of the kidney using sliced pig kidney sections. In the future, we plan to collect data more similar to actual surgery using whole pig kidneys and improve the heat conduction equation.

Keywords: Partial nephrectomy · Cold ischemia · Temperature prediction model

1 Introduction

Partial nephrectomy is now established as the standard treatment for small renal cancer. In partial nephrectomy, only the tumor and surrounding tissue are removed, thus preserving renal function after surgery. Renal ischemia is commonly used to temporarily block blood flow to the kidney to control bleeding during tumor resection. However, renal ischemia is associated with renal dysfunction. Ice slush is placed around the kidney during renal

M. Kurosu and A. Hashizume (Eds.): HCII 2023, LNCS 14014, pp. 87–95, 2023.
https://doi.org/10.1007/978-3-031-35572-1_6

ischemia to cool the kidney (cold ischemia) to prevent renal dysfunction. Cold ischemia has been reported to be effective in preserving renal function in the postoperative period when the duration of ischemia time is prolonged [1].

The appropriate deep renal temperature for the preservation of renal function is approximately 20 °C, and it has been confirmed that cold ischemia in open human abdominal surgery can cool the kidney to 20 °C in approximately 10 min [2]. At present, the only reported method for measuring deep renal temperature is the invasive method of puncturing the kidney with a needle-type thermocouple. Therefore, when cold ischemia is performed in surgery, the surgeon only waits 5–10 min after the start of cooling without measuring the deep renal temperature. However, the rate at which the kidneys are cooled is affected by the thickness of the perirenal fat tissue and the extent of the kidney exposure, so the time required for adequate renal cooling varies markedly from case to case, ranging from 3–20 min [3]. This case-to-case difference is important because excessive or inadequate cooling can adversely affect postoperative renal function.

In a previous study, we reported on a 2D thermal diffusion model based on thermographic measurements of thermal diffusion in liver tissue. This allowed them to successfully quantify thermal damage inside biological tissue caused by electrocautery using heat conduction simulation [4]. We came up with the idea that noninvasive prediction of deep kidney temperatures would be possible by applying the methods used in this study to quantify thermal damage inside living tissue using thermal diffusion measurement with a thermal imaging camera and thermal conduction simulation.

In this research, we propose a non-invasive method for deep kidney temperature measurement, which predicts the deep kidney temperature by estimating the thermal diffusivity from the temperature data of a needle thermocouple and a 3-dimensional unsteady heat conduction simulation.

2 Implicit Solution of the Heat Conduction Equation

In this research, the three-dimensional unsteady heat conduction equation:

$$\frac{\partial T}{\partial \mathrm{t}} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \quad (1)$$

is discretized by the implicit Gauss-Seidel method into equation:

$$\frac{T^n_{x,y,z} + C_x + C_y + C_z}{1 + 2\alpha\Delta t(\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2})} \quad (2)$$

Simulations are performed using this equation. In this equation,

$$C_x = \frac{\Delta t \times \alpha}{\Delta x^2}\left(T^{n+1}_{x-1,y,z} + T^{n+1}_{x+1,y,z}\right) \quad (3)$$

$$C_y = \frac{\Delta t \times \alpha}{\Delta y^2}\left(T^{n+1}_{x,y-1,z} + T^{n+1}_{x,y+1,z}\right) \quad (4)$$

$$C_z = \frac{\Delta t \times \alpha}{\Delta z^2}\left(T^{n+1}_{x,y,z-1} + T^{n+1}_{x,y,z+1}\right) \quad (5)$$

T represents temperature, x, y, and z are coordinates, and α is thermal diffusivity.

3 Cooling of Pig Kidney and Measurement of Temperature Change

To estimate deep temperature using heat conduction simulation, renal temperature data during cold ischemia is required as original data. In this research, an experimental device was constructed to measure renal temperature changes during cooling (see Fig. 1). This device is fabricated with a 3D printer (Snapmaker2.0 F250), and a needle thermocouple can be vertically punctured and fixed at the specified position on a renal section. The puncture position was set at the center of the cooling surface of the porcine kidney section as the origin, with (x, y, z) = (0, 0, 3) for 1ch, (0, 0, 6) for 2ch, (0, 0, 9) for 3ch, and (0, -3, 6) for 4ch, for a total of 4 needle thermocouples for measurement (see Fig. 3). To suppress external temperature changes, the kidney sections were covered with Styrofoam and the space between them and the experimental device was filled with Styrofoam. Ice was placed on the upper surface of the kidney to reproduce cooling by an ice slush, while the lower portion was in contact with air. Pig kidney slices were used for cooling, one with renal capsule and the other without renal capsule, and temperature data were measured four times by taking two samples from each specimen. Pig kidney sections were removed and cut into cubes of approximately 10 mm per side, and measurements were started when the temperature was stable. Four seconds after the start of temperature measurement, ice was placed on top of the experimental device as shown in Fig. 2 to start cooling, and was maintained until the end of the measurement. In this experiment, 88598AZ EB needle thermocouples were used. Temperature data was output every second for each channel. The temperature measurement data for 10 min is shown in Fig. 4.

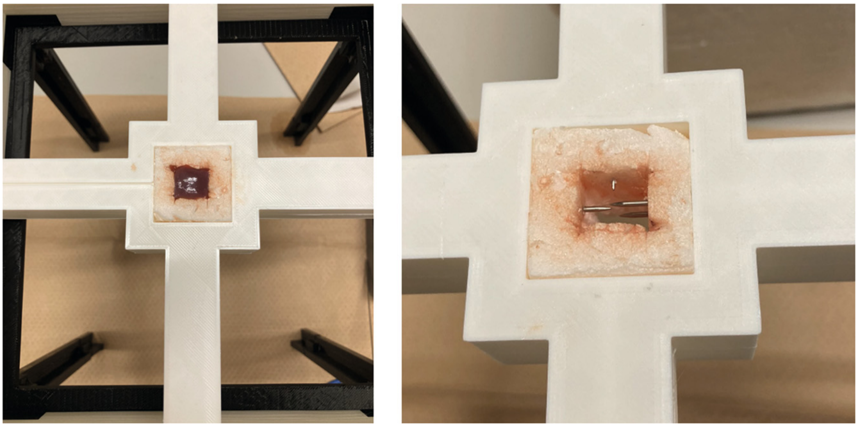

Fig. 1. Experimental device to measure renal temperature changes.

Fig. 2. Ice was placed on top of the experimental device.

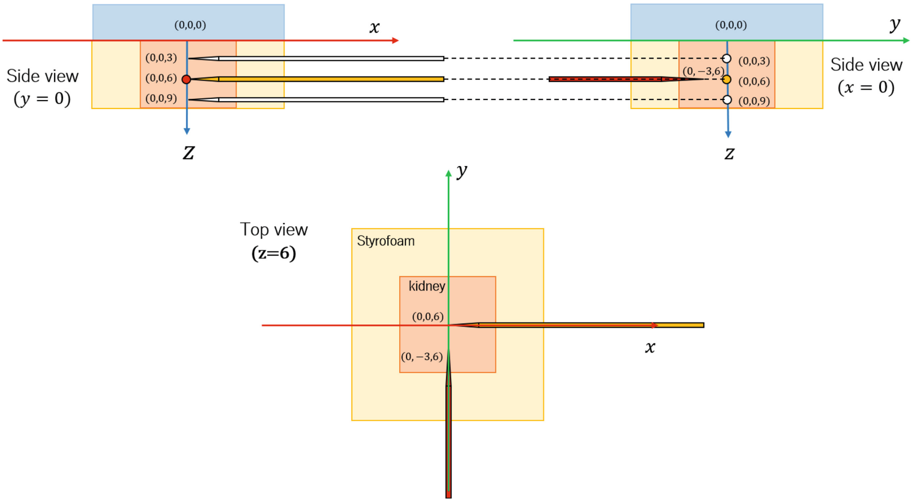

Fig. 3. Measurement of pig kidney section using four needle thermocouples.

4 Comparison of Simulated Data and Measured Data

4.1 Calculation of Thermal Diffusivity

By comparing the measured temperature data with the simulated temperature prediction data, an estimate of the thermal diffusivity was calculated for the temperature data in cooling the pig kidney shown in Fig. 4. The object of this simulation was a cube shape with 10 mm per side, similar to the pig kidney section, and Δx, Δy, and Δz were set to 0.1, respectively.

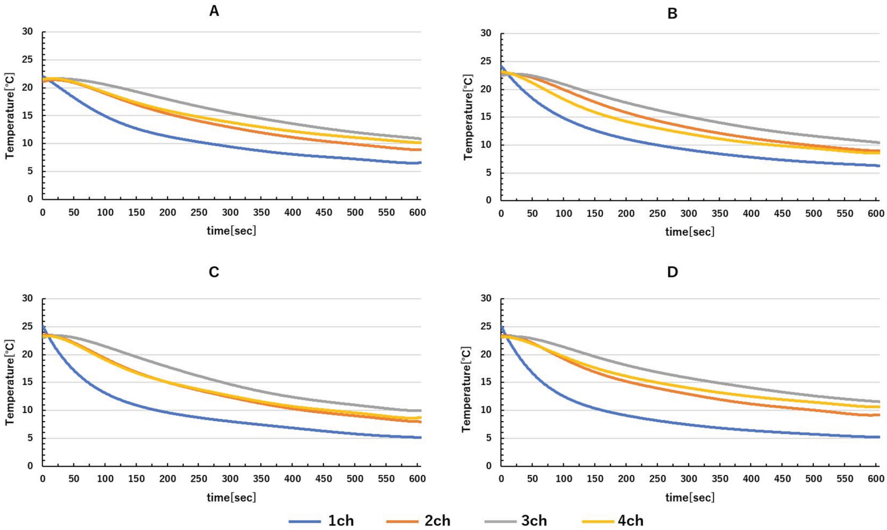

Fig. 4. Temperature change during kidney cooling. Kidney with renal capsule (A and B) kidney without renal capsule (C and D)

4.2 Difference Value Between Simulated and Measured Data

The initial temperature at each point was the initial temperature at the start of measurement with a needle thermocouple in the original data. Assuming that the organ was being cooled with ice, the temperature distribution was calculated when the upper surface of the object was continuously cooled to 0 °C from the start to the end of the simulation with $\Delta t = 0.1$s. The simulation time was 600 s. The thermal diffusivity was changed in the range of 0.0005 to 0.003 cm^2/s in 0.0001 cm^2/s increments based on the estimates obtained by the authors' previous study, and temperature data were generated. The estimated value in this study refers to the thermal diffusivity with the smallest temperature difference from the original data. Python 3 was used for the simulations. For each thermal diffusivity, Fig. 5 shows the results of comparing the difference every 0.1 s between the temperature data from the theoretical needle thermocouple and the temperature data from the simulation. The average of the differential temperature data values in 1ch to 3ch was calculated as the differential value for each thermal diffusivity. The measured temperature data was every 1 s, and since it was used to measure to one decimal place, the measured data was approximated by a polynomial equation with a seventh order function, and the data was every 0.1 s. The values were close to those of the original data. Comparing the measured original data and the simulated temperature data, the simulated temperature data showed a more rapid decrease in temperature.

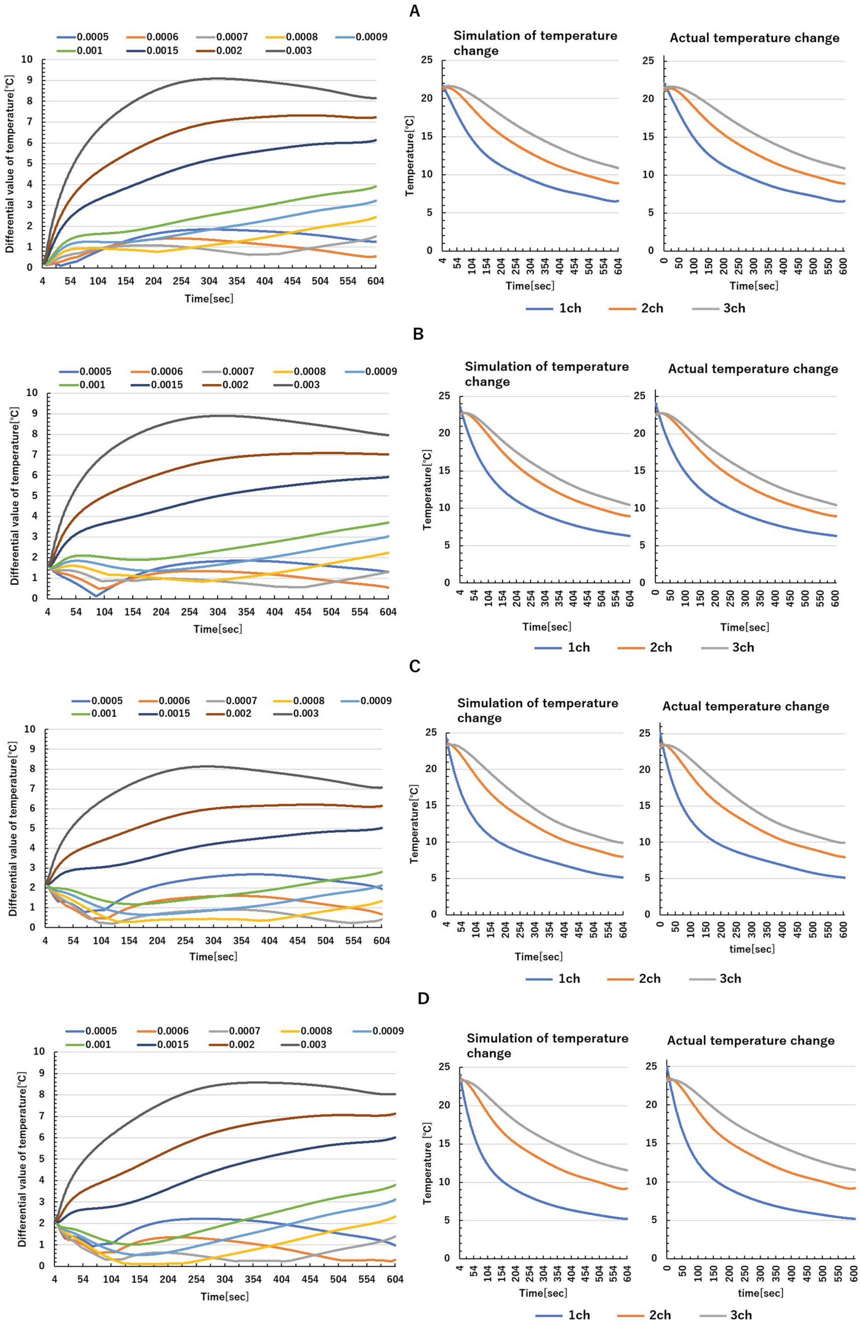

Fig. 5. Differential value of the temperature of each kidney (Left). Simulation of temperature change (Center). Actual temperature change (Right). Kidney with renal capsule (A and B). Kidney without renal capsule (C and D)

5 Future Plans

5.1 Measurement of Temperature Change During Kidney Cooling Using Whole Pig Kidney

Accurate deep temperature evaluation is difficult based on the thermal diffusivity of pig kidney sections alone since kidney cooling includes the effects of the area of the kidney surface being cooled, the surrounding air, urinary tract tissue, and adipose tissue. Therefore, it is necessary to modify the thermal diffusivity and model based on temperature changes in the whole pig kidney. A needle thermocouple is punctured into a pig kidney at a depth of 1cm from the renal surface to measure temperature. This depth of puncture allows measurement of deep renal temperature [5] (see Fig. 6). The pig kidney is cooled with an ice slush, and when the deep renal temperature reaches 20 °C, the ice slush is removed and the renal surface temperature is measured with a thermal imaging camera to confirm the relationship with the deep temperature (see Fig. 7). The thermal diffusivity and model are modified so that the surface and deep temperature results are consistent with the simulation results.

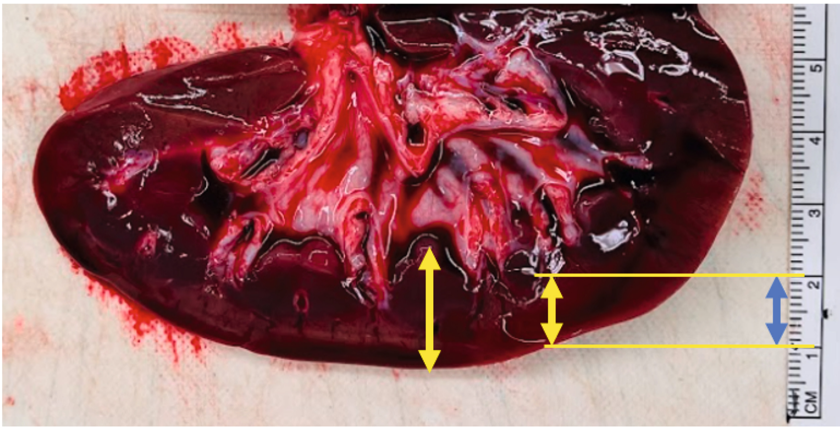

Fig. 6. Depth for proper measurement of the deep temperature of pig kidney parenchyma.

5.2 Measurement of Temperature Change Using a Living Pig Kidney.

In vivo, the response to renal cooling is expected differently depending on blood flow and surrounding organs in contact with the kidney, so modification of the temperature prediction using living animal data is necessary. Temperature measurements are made after reproducing renal cold ischemia in open surgery. The rest of the flow is the same as in 5-1.

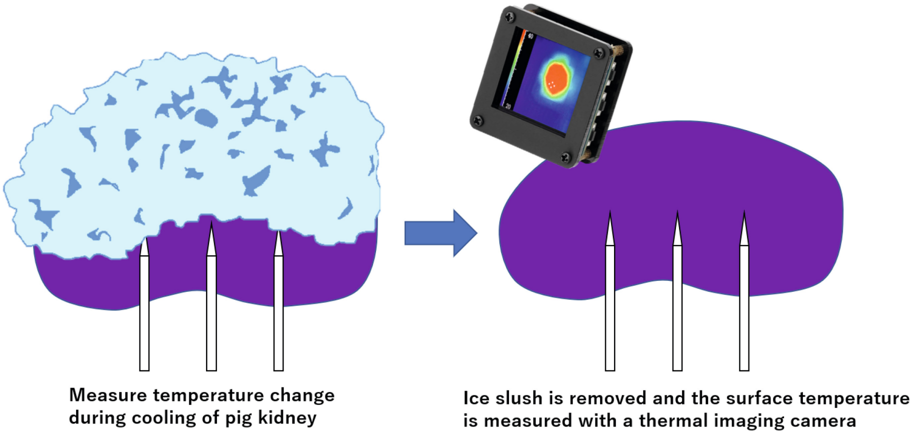

Fig. 7. Temperature measurement of the whole pig kidney.

6 Discussion

Surgical treatment for renal cell carcinoma used to be radical nephrectomy, in which the entire kidney was removed. Partial nephrectomy emerged as the widely recommended treatment for small renal tumors after better oncologic and functional outcomes than radical nephrectomy was published [6]. In the 1960s, the technique of "cold ischemia," in which the kidney is cooled, greatly advanced the use of partial nephrectomy[7]. In the 1970s, many reports were published on the use of needle thermometers inserted into human kidneys during surgery to measure the optimal deep kidney temperature for cold ischemia [2]. Since it is generally known that the appropriate deep kidney temperature is reached after approximately 10 min of renal cooling, and since minimally invasive surgery has been pursued, few reports of deep kidney temperature measurement using a needle thermometer puncture have been reported. However, if ice slush is placed around the kidney for cooling, the cooling rate varies depending on the thickness of the fat around the kidney and the extent of exposure to the renal surface. It has been reported that the time required to cool the kidney to a sufficient temperature varies greatly from case to case [3]. Given this current situation, a technique to noninvasively measure deep kidney temperature is needed to further improve the outcome of partial nephrectomy.

Although this study aims to improve outcomes in partial nephrectomy, the minimally invasive technology for predicting deep organ temperatures has potential applications in other fields. For example, in renal transplantation, the donor kidney must be maintained at a low temperature until the blood flow is reperfused. However, since temperature measurement by puncture with a needle thermocouple, which can damage the donor's kidney, is not appropriate, only the surface temperature is almost always measured [8]. Therefore, if a predictive model for deep organ temperature is developed, it could be applied in transplant surgery, where organ cooling is required.

The limitation of this study is the difficulty of collecting temperature measurement data using living kidneys. The best way to more accurately predict changes in deep kidney temperature up to 20 °C would be to conduct experiments using live human kidneys. However, this is ethically difficult. Instead, in this study, we used pig kidney sections to estimate the thermal diffusivity. In the future, we plan to conduct experiments using whole pig kidneys. It has been reported that the morphological characteristics of pig kidneys have many similarities and few morphological differences with human kidneys [9], and the experimental data using whole pig kidneys have a high potential for application to actual surgery. In addition, the appropriate deep temperature for the preservation of renal function is not required to be exactly 20 °C. Depending on the report, the appropriate renal deep temperature ranges from 15 °C–20 °C [2, 10]. In light of these considerations, the experimental technique used in this study is considered acceptable.

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