

Article

The Design of an Automatic Temperature Compensation System through Smart Heat Comparison/Judgment and Control for Stable Thermal Treatment in Hyperthermic Intraperitoneal Chemotherapy (HIPEC) Surgery

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Abstract: After surgery for ovarian cancer or colorectal cancer, residual tumors are left around. A practical way to treat residual tumors is to destroy them with heat by injecting high-temperature drugs into the abdominal cavity. The injected medicinal substances are induced to flow out of the abdominal cavity; then, the spilled drug flows back into the abdominal cavity through feedback. During this process, the heat starts to decrease; thus, the treatment performance reduces. To overcome this problem, this study compares and assesses the temperature needed to maintain the heat for treatment and transmits a command signal to the heat exchanger through a look-up table (LUT). When the temperature decreases during the circulation of medications leaking out of the abdominal cavity, the LUT transmits a control signal (T_p) to the heat exchanger, which increases or vice versa. However, if the temperature (T_o) is within the treatment range, the LUT sends a T_s signal to the heat exchanger. This principle generates a pulse signal for the temperature difference (T_{dif}) in TC by comparing and determining the temperature (T_o) of the substance flowing out of the abdominal cavity with the reference temperature (T_{ref}) through the temperature comparator (TC). At this time, if the signal is 41 °C or less, the LUT generates (heats) a T_p signal so that the temperature of the heat exchanger can be maintained in the range of 41 °C to 43 °C. If the T_{dif} is 44 °C or higher, the LUT generates (cools) the T_a signal and maintains the temperature of the heat exchanger at 41–43 °C. If the T_{dif} is maintained at 41–43 °C, the LUT generates a T_x signal to stop the system performance. At this time, the TC operation performance and T_{dif} generation process for comparing and determining the signal of T_o and T_{ref} for drugs leaking out of the abdominal cavity is very important. It was observed that the faster the response signal, the lower the comparison and judgment error was; therefore, the response signal was confirmed to be 0.209 μ s. The proposed method can guarantee rapid/accurate/safe treatment and automatically induce temperature adjustment; thus, it could be applied to the field of surgery.

Keywords: HIPEC surgery; high-temperature drug; cancer; LUT; temperature adjustment



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1. Introduction

As of 2017, there have been 232,255 cases of domestic cancer incidence, with an estimated cancer incidence rate of approximately 1,867,405 [1]. Therefore, approximately 3.6% of patients were diagnosed with cancer, which was the leading cause of death among men and women in 2018 [2]. After cancer surgery, a high probability of recurrence (within 5 years) at more than 50% exists due to the residual tumor tissue.

Chemotherapy is administered concurrently to reduce the chance of recurrence. However, due to its side effects, patients experience difficulties during treatment. Thus, new treatment methods for eliminating the probability of recurrence within 5 years have been studied and are currently being used in many medical institutions [1–6]. Most of the thermal death methods for tumors include HIFU (High-Intensity Frequency Ultrasonic) treatment, laser treatment, and radiofrequency treatment [3–6]. Among them, the high-frequency treatment causes hyperthermia by an antenna that heats through radio and microwave radiation and damages cancer cells with heat.

In particular, HIFU can be applied to targeted therapy and can necrotize tumors using high heat [7]. This method can destroy cancer cells by generating immediate heat. However, it has the side effect of damaging the skin and its surrounding tissues [7]. Laser treatment causes a chemical reaction between light and oxygen to generate instant heat [8]. This method damages the micro-vessels around cancer cells to minimize patient pain and block the supply of nutrients to cancer tissue. These treatments cause side effects such as skin hypersensitivity, edema, pain, and pigmentation [9]. Laser treatment can also damage the skin [8,9].

Radiofrequency treatment is a method for irradiating cancer tissue with electromagnetic waves to generate heat, increase the metabolic rate in the body, and suppress the proliferation of cancer cells to destroy them [10]. Therefore, the radiofrequency treatment has no side effects such as nausea, vomiting, anorexia, weight loss, digestive disorders, and hair loss. Nevertheless, red spots may occur on the skin tissue where the electrodes are attached, and side effects such as slight burns, scars, inflammation, and lumps may occur in the fat layer [10,11].

In addition, HIFU therapy, laser therapy, radiofrequency therapy, and radiation therapy methods are used for the targeted treatment of tumors and are often used in combination with chemotherapy to increase the effectiveness of treatment. Chemotherapy is administered intravenously; however, various treatment systems that allow for the direct exposure of anticancer drugs are currently under investigation and development.

Among them, hyperthermic intraventricular chemotherapy (HIPEC) surgery is a system that uses high-temperature anticancer drugs and injects them into the abdominal cavity, and it is a treatment method that directly exposes anticancer drugs to residual tumors after surgical operation. Hyperthermia using high-temperature anticancer drugs has been shown to be highly effective against cancer cells when administered at temperatures ranging from 41 °C to 43 °C Celsius, whereas normal tissues can be damaged by temperatures above 46 °C Celsius [12–14]. This hyperthermia increases the sensitivity of cancer to chemotherapy by increasing the penetration of chemotherapy on the peritoneal surface and impairing DNA repair. In addition, hyperthermia has direct cytotoxic effects by inducing apoptosis, activating heat shock proteins that act as receptors for natural necrotic cells, inhibiting angiogenesis, and promoting protein denaturation [15]. The problem with these cancers is that the 5-year survival rate is difficult to expect, and the risk of recurrence is high; therefore, the purpose of HIPEC surgery is to completely remove the remaining cancer cells. The 5-year survival rate of gastric cancer patients undergoing HIPEC surgery increased by more than 61% compared to patients undergoing laparoscopic surgery [16–19]. Similarly, the 5-year survival rate of peritoneal cancer patients increased by over 48.5% compared to those undergoing laparoscopic surgery. Following colon cancer surgery, patients who received chemotherapy had a 41% recurrence rate at the 5-year survival mark due to peritoneal metastasis [20]. However, HIPEC surgery resulted in a 53% reduction in its recurrence rate at the 5-year survival rate.

However, if a 41 °C to 43 °C medication is injected into the abdominal cavity while using a hyperthermia system in the operating room, the intraperitoneal temperature is lowered to below 41 °C, and the therapeutic effect of hyperthermia cannot be enhanced [12].

In this study, when administering high-temperature medications in the abdominal cavity, the thermal compensation based on the temperature measurement could maintain the temperature of the drug at 41–43 °C by monitoring the temperature state of the drug and actively increasing the heat when the temperature decreased. Moreover, we developed the control method design.

A control signal was generated to compensate for the temperature difference in the look-up table (LUT) module by comparing the temperature of the drug flowing out and the reference heat ranging from 41 °C to 43 °C. Hence, this study presents a method that compensates for heat according to the control signal.

2. Materials and Methods

2.1. Background of HIPEC Surgery

HIPEC treatments are categorized into open and closed techniques, as shown in Figure 1. The closed technique involves inserting and securing the inflow and outflow catheters into the abdominal cavity before injecting chemotherapy, then closing the abdominal wall and injecting the hot chemotherapy solution to allow for perfusion into the abdominal cavity. The main disadvantage of the closed technique is the uneven distribution of chemotherapeutic agents in the abdominal cavity, which results in fluid retention and the accumulation of toxic concentrations of drugs and heat [21].

In comparison, the HIPEC open method or “coliseum” technique involves injecting the hyperthermic chemotherapy solution into the abdominal cavity while the abdomen is open. The advantages of the open approach include the surgeon’s direct access to the abdominal cavity with an inflow catheter during the administration of the hyperthermic agent, which allows for the rapid and uniform control of the temperature and distribution of the drug in the abdominal cavity by manipulating fluids and the bowel. Care also needs to be taken to ensure that all peritoneal surfaces are uniformly exposed during treatment and to avoid dangerous temperatures or excessive exposure to normal tissue. The potential disadvantages of this procedure include the rapid loss of heat, which requires more effort to maintain ideal temperatures, and the potential exposure of the surgeon and operating staff to chemotherapeutic agents by direct contact and aerosolized particles [22].

For the use of these techniques, a HIPEC system consists of a fluid box, a heat exchanger, and a filter, as shown in Figure 2. It is further composed of inlet and outlet catheters that are connected to the system [15,21–23].

The heat exchanger operates to heat the drug to a high temperature. The medicinal substances flow into the heat exchanger and are heated up to 48 °C. The heated drug is introduced into the abdomen through an inflow catheter, and the abdominal temperature remains between 41 °C and 43 °C for 120 min, damaging cancer cells remaining in the abdomen [15,21,24].

The anti-cancer drug that flows into the abdomen continues to flow into the fluid box through the filter and outflow catheter. Additionally, the medicinal substances that flow in are repeatedly circulated through the inflow and outflow of the abdomen through the heat exchanger and inflow catheter. At this point, the filter operates to filter out the mixed residues from the abdomen in the drug leaked from the outflow catheter. When performing thermal treatment using the HIPEC system, the temperature of the abdomen should be maintained between 41 °C and 43 °C [15,21–24]. However, if the medication passes through the line in the process of repeating the inflow and outflow of the medicinal substances or if thermal treatment is performed through open surgery, the temperature of the drug in the abdominal cavity can drop to 36 °C. If the drug temperature drops to below 41 °C, the tumor does not undergo necrosis and rather results in poor treatment. Therefore, for efficient thermal treatment, a functional device for maintaining the temperature of the interior of the abdominal cavity at 41 °C to 43 °C is required. In the operating room, as

shown in Figure 3, if the temperature in the abdominal cavity actually decreases below 41 °C, heat is manually controlled [21–24].

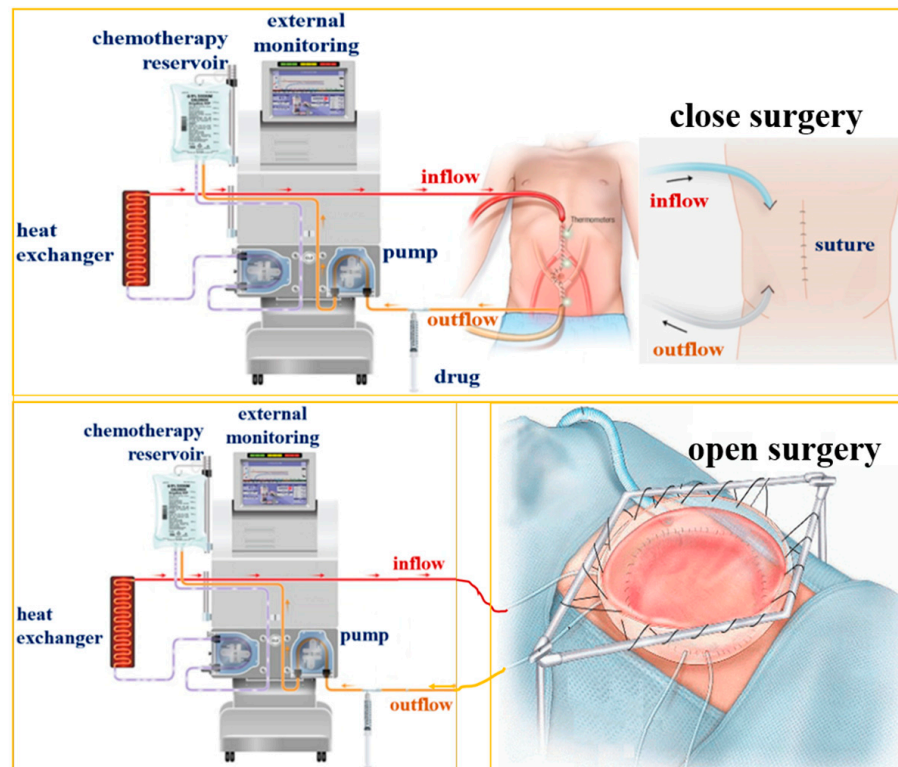


Figure 1. Concept of HIPEC surgery [24].

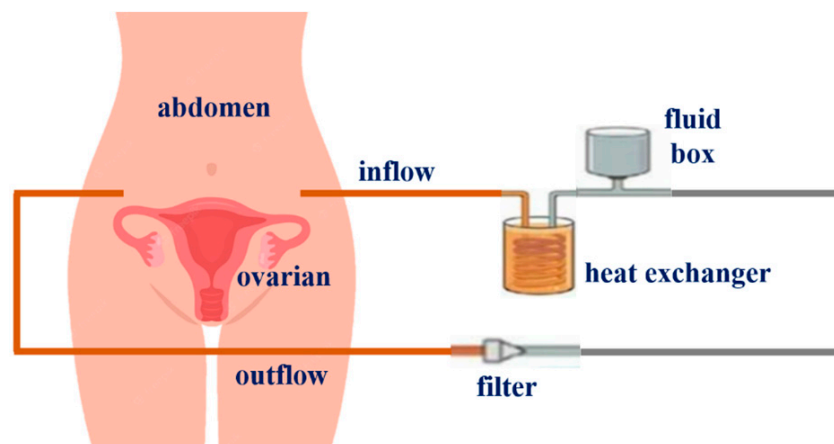


Figure 2. Principle of drug delivery during HIPEC surgery.

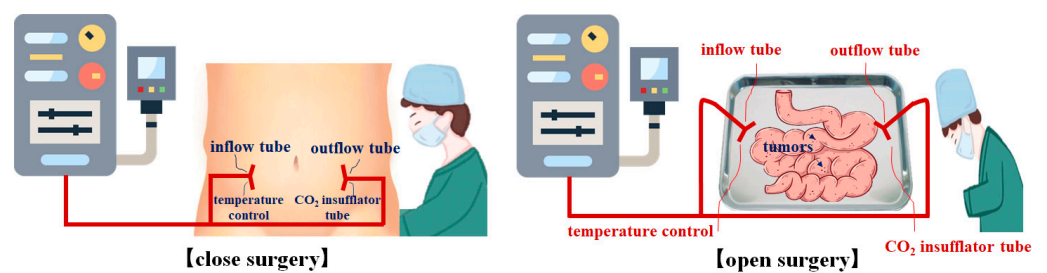


Figure 3. HIPEC surgery (operating room) [21].

If the temperature increases by more than 43 °C, the treatment process can be stopped until the temperature decreases [15,21–24]. The abovementioned actions are cumbersome and lead to time and human force consumption. Thus, there is a need to examine an automatic control method to adjust the proper temperature by real-time temperature sensing and compensation, which is capable of maintaining the treatment temperature.

2.2. Design of HIPEC System for Temperature Comparison and Control

As shown in Figure 4, the reference heat generator (HG) that is intended to maintain the intraperitoneal medicinal substances temperature generates heat (TR) within a range of 41–43 °C. This heat (TR) is converted into an analog signal through a temperature-to-voltage converter (TVC).

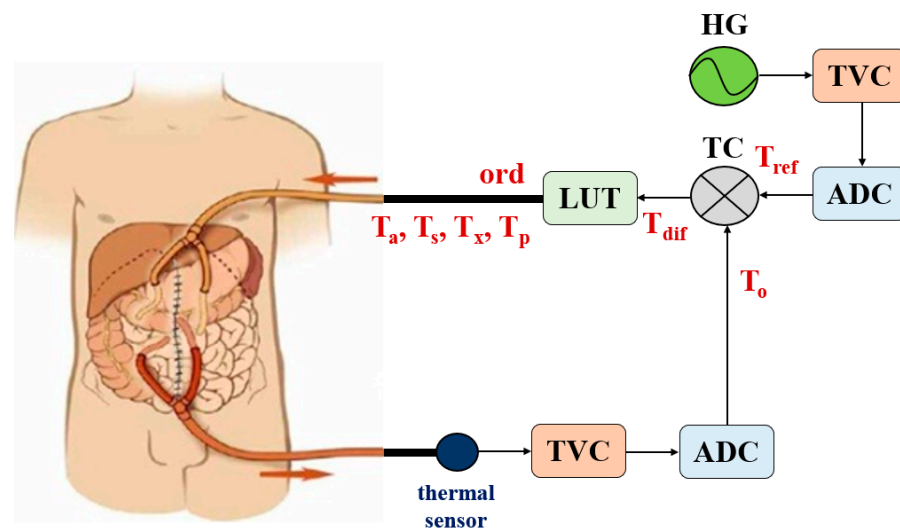


Figure 4. Block diagram of proposed system.

The analog signal provided by the TVC is converted into a pulse train (T_{ref}) by an analog-to-digital converter (ADC). The heat (T_o) leaking from the abdominal cavity is detected by the temperature sensor. The detected temperature T_o is converted into an analog signal through the TVC [24]. This analog signal is converted into a pulse signal via ADC for feedback. The T_o signal is converted into a pulse signal, which is input into the TC and generates a T_{dif} signal, as shown in Equation (2) through the comparison and judgment with T_{ref} as shown in Equation (1), where h and χ represent Joule's heat and thermal conductivities with respect to heat T_o , respectively.

$$T_o(t) = T_{dif} \sin \left[T_{ref}(t) + h(t) \right] = \chi T_{dif}(t) \sin \chi T_{ref} h(t) + \frac{1}{\sqrt{\frac{1 + \tan\left(\frac{h_{dif}(t)}{2}\right)}{1 - \tan\left(\frac{h_{ref}(t)}{2}\right)}}} \left[\ln \left(1 - \frac{\left[1 + \tan\left(\frac{h_{dif}(t)}{2}\right) \right]}{4\pi \left[1 - \tan\left(\frac{\chi T_{ref} h(t)}{2}\right) \right]} \right) \right] - \left[2 \ln \frac{T_{ref}}{T_{ref} - T_{dif}} \right] \quad (1)$$

$$T_{dif}(t) = \chi T_{ref} h(t) - \chi T_o(t) = \chi T_{ref} h(t) - 2\pi \chi T_o \int_{-\infty}^{\infty} T_o dt = \int_0^t T_o(h(t) - 1) dt = 2\pi \chi T_{ref} h \int_0^t T_o dt \quad (2)$$

In Equation (1), changes occur over time in a limited temperature range by the function of $T_{ref}(t)$. However, T_{ref} changes within a temperature range of 41–43 °C. In this case, the temperature range must have excellent thermal conductivity (χ) in order to accurately maintain 41–43 °C. That is, h is defined as a Joule heat function for fixing a temperature range of 41–43 °C. T_{ref} with excellent thermal conductivity (χ) increases its temperature by $\tan$ over time, and the temperature change in T_{ref} increases by $\tan(t)$ and is maintained within a certain range through saturation. This allows changes to be made, allowing the temperature to rise, fall, and be maintained over time. Therefore, the sum of T_{ref} and T_{dif} ($T_{ref} + T_{dif}$) can observe the T_o temporal state of change. T_{dif} arises from the difference

between T_{ref} and T_o . At this time, if the temperature (T_{ref}) that changes over time and the temperature (T_o) that changes over time in the $h(t)$ function range with excellent thermal conductivity (χ), they generate a temperature difference in TC, $T_{dif}(t)$ that changes from 0 to t , as shown in Equation (2).

The signal (T_{dif}) from the TC is input to a lookup table (LUT). As shown in Table 1 and Figure 5, the LUT generates a control command signal (ord) through internal operations. This command signal (ord) is delivered to a heat exchanger, which heats up (T_p), reduces heat (T_a), stops operating (T_x), or maintains its current state (T_s). If T_o is below 41 °C, T_{dif} for this temperature (41 °C) passes to the LUT, which generates signal T_p to command the heat exchanger. The heat exchanger compensates the heat to reach the therapeutic temperature range (41–43 °C). If T_o is within this range, the LUT generates signal T_s (hold state), and the operation of the heat exchanger does not change. If T_o is above 44 °C, the LUT generates signal T_a , and the heat exchanger reduces the temperature. If T_o exceeds 46 °C, the LUT generates signal T_x , and the heat exchanger stops operating (i.e., stop heating and wait).

Table 1. Design of the look-up table (LUT).

Temperature Range	Signal to LUT			Status of Temperature	
	T_{ref}	T_o	T_{dif}	ord	TC
40 °C	1	0	–	up	T_p
41–43 °C	0	0	1	hold	T_s
44 °C	0	1	0	down	T_a
>46 °C	1	1	x	stop operation	T_x

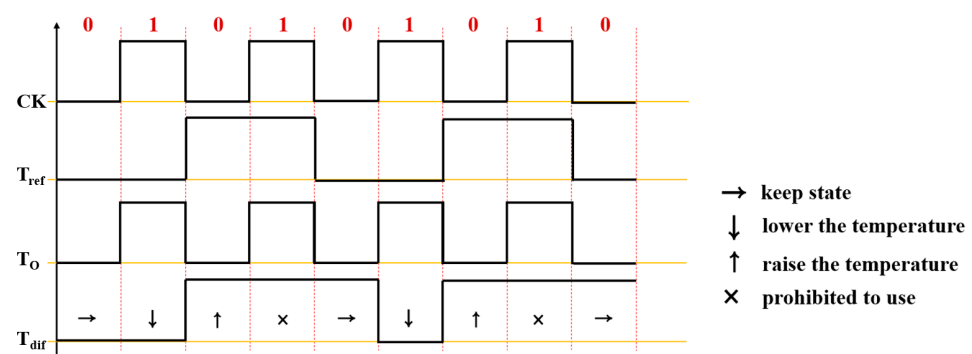


Figure 5. Logic signals for temperature comparison and decision by the proposed system.

As shown in Figure 5, T_{ref} and T_{dif} repeat 0 and 1, respectively, and the signal is input to the TC. T_{dif} is divided into state maintenance, temperature reduction (0), temperature increase (1), and operation interruption (x).

Figure 6 shows the circuit for the comparator and LUT, which includes a non-exclusive OR gate.

When the medication flows out of the abdominal cavity, the temperature (T_o) flowing out is compared with the temperature of the T_{ref} through the TC to the output T_{dif} . At this time, TC is in charge of the performance that generates T_{dif} through the comparison and judgment of T_{ref} and T_o . T_{dif} is then input to LUT to generate the command signals (ord) of T_a , T_p , T_s , and T_x . The signals (T_p , T_s , T_a , and T_x) command the heat exchanger for temperature control. The proposed system is a chemical surgical treatment that removes cancer by injecting high-temperature medicinal substances into the abdominal cavity. The drug maintains the drug's temperature in the range of 41–43 °C through intraperitoneal injection and drainage. The drug circulates through a heat exchanger. These performances are automatically and repeatedly controlled until the treatment is complete.

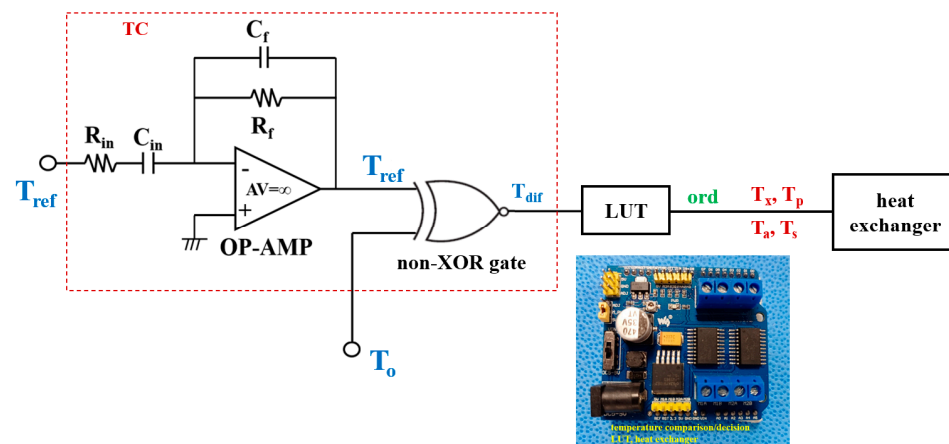


Figure 6. Equivalent circuit of proposed system for temperature comparison, control and the implemented circuit.

3. Experimental Results

For the performance test of the substance temperature maintenance, we conducted an experiment that comprised the proposed module, beaker, thermal imaging camera, and temperature measuring device, as shown in Figure 7. This study was not a clinical trial but an experiment to test the performance of the module and evaluate whether the heat temperature could be accurately controlled. Therefore, we aimed to obtain results on the accuracy, reproducibility, and performance reliability of temperature control. Additionally, the performance test evaluation to minimize the response error (delay) for control was reviewed.

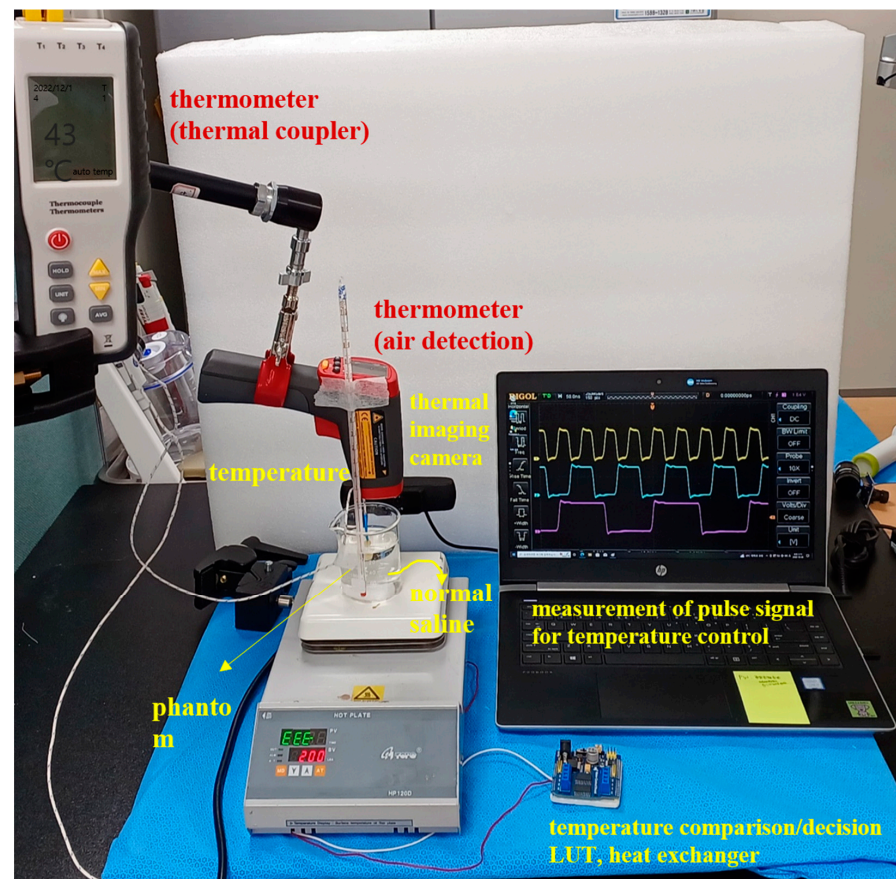


Figure 7. Experimental environment and configuration system.

The peritoneal cavity could be substituted with a beaker (100 mL) when filled with normal saline (40 cc). The temperature range of normal saline is 41–43 °C; if this was below 41 °C or above 43 °C, the TC and LUT were operated and controlled to match this range. Thus, it was simulated similarly to the HIPEC surgical procedure.

The designed temperature control module and the beaker were connected with a catheter, as shown in Figure 7, and the catheter functioned as the inflow and outflow of the beaker. An external monitoring system measured the temperature conditions and thermal compensation adjustments.

The system determined the pulse signals according to the current drug temperature to reduce, increase, or maintain the temperature. In temperature tests, the pulse signal range of T_{ref} was stably maintained in the range of 41–43 °C, as shown in Figure 8. If the temperature of the signal T_o was reduced to 41 °C or less, the pulse signal of the different output from the TC was set to transmit to the LUT. Thus, the LUT generated a command signal (*ord*) for the T_p signal and took measures to heat it in the heat exchanger.

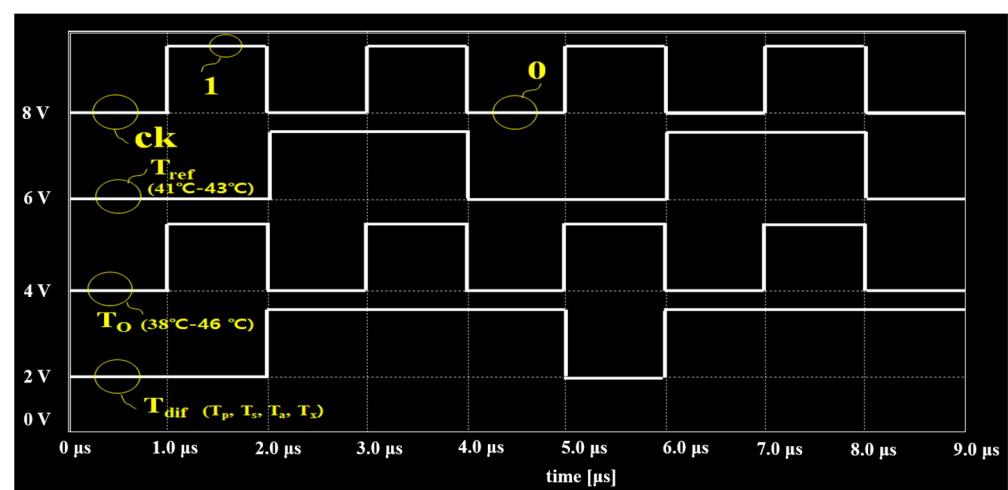


Figure 8. Output of pulse logic signal for the comparison and control of temperature based on TC.

The proposed module configured T_{ref} and T_o signals before their input to TC. The TC- T_{dif} output worked to output a pulse signal for the drug temperature state. As shown in Figures 8 and 9, when the pulse signal ($T_{dif} = T_{ref} = T_o$) corresponding to the range of T_{dif} from 41 °C to 43 °C was output, the output pulse signal was 1. At this time, as shown in Figure 8, the signal of 1 was in the form of a pulse corresponding to 4 to 5 μs. If the T_{dif} ($T_{dif} = T_o/T_{ref}$) signal output from the TC was below 41 °C, the pulse signal of T_{dif} corresponded to 1, and this pulse signal corresponded to a period of 2–4 μs. If the signal output from the TC T_{dif} ($T_{dif} = T_o/T_{ref}$) corresponded to 44 °C or higher, the pulse was 0. The period of this signal is 1–2 μs. The signal output by T_{dif} ($T_{dif} = T_o/T_{ref}$) in TC was a pulse signal of 1 corresponding to 46 °C or higher, and the period of this pulse signal corresponded to 7–8 μs. Therefore, the pulse signal of 1 (4–5 μs) generated from T_{dif} was delivered to the LUT, and the LUT generated a T_s signal (41–43 °C); therefore, the substance was injected into the abdominal cavity without being transmitted to the heat exchanger.

The pulse signal corresponding to 1 (2–4 μs) and generated from T_{dif} was delivered to the LUT. The LUT generated a T_p signal (<41 °C). The T_p signal provided the heat exchanger with a command signal for heating to maintain a temperature range of 41 °C to 43 °C. The pulse signal of 0 (1–2 μs) generated from T_{dif} was delivered to the LUT. The LUT generates a T_a signal (>44 °C). The T_a signal delivers a command signal for cooling to maintain a temperature from 41 °C to 43 °C in the heat exchanger.

The pulse signal of 1 (7–8 μs) generated from T_{dif} was delivered to the LUT, and the LUT generated a T_x signal (>46 °C), which transmitted the T_x signal to the heat exchanger. Therefore, the system operation was stopped until the intraperitoneal injection temperature

range changed from 41 °C to 43 °C. Therefore, the command signal data transmitted from the LUT to the heat exchanger were T_p , T_s , T_a , and T_x .

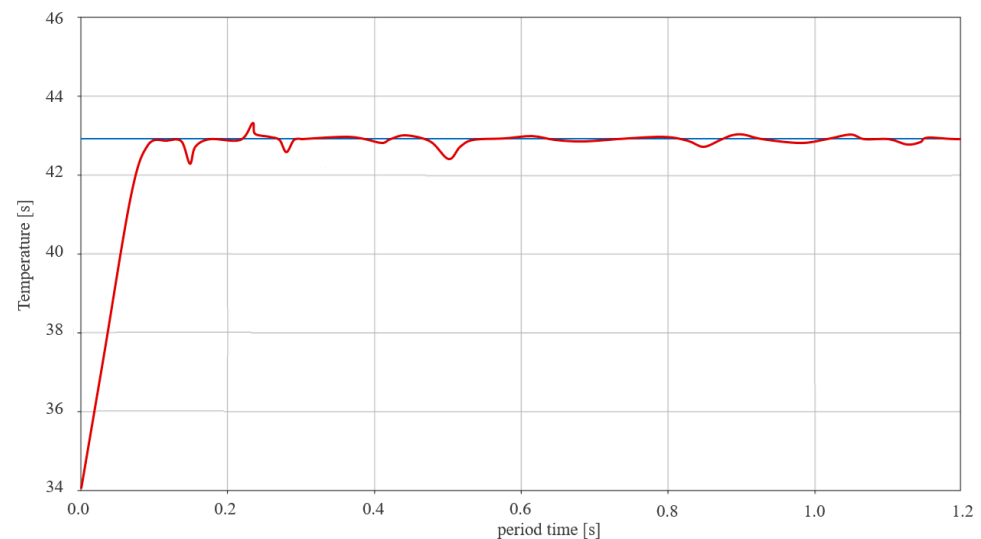


Figure 9. Output temperature obtained from the comparison and control based on TC.

More specifically, if the logical function of the D-flip flop was considered in the experiment, the control process of TC and data learning of LUT was added to the heat exchanger using a binary signal and based on a pulse waveform. Therefore, the temperature of the drug in the heat exchanger could be controlled, as shown in Figures 9 and 10. If T_{ref} always maintains a constant value in the range of 41–43 °C ($T_{ref} = 0$), the range of the temperature of the medicinal substance (T_{dif}) flowing out of the beaker (peritoneal cavity) is 41–43 °C ($T_o = 0$), as shown in Figure 10. At this point, the temperature difference ($T_{dif} = T_o = T_{ref}$) generated in the comparator could provide a value of 1. Thus, the temperature of the substance in the heat exchanger remained unchanged, and the temperature range of T_{dif} was between 41 °C and 43 °C. In the experimental process of the temperature difference generation for the TC output, T_{ref} and T_o were assumed to be 38 °C ($T_o = 0$) and 41 °C ($T_{ref} = 1$), respectively, and then these two pulse signals were set to be input to TC. The output (T_{dif}) of the TC generated a pulse signal ($T_{dif} = \text{random signal}$) in which a temperature difference of 3 °C occurred. When these signals were input to the LUT, the LUT recognized a temperature difference of 3 °C. The LUT, which recognized a temperature difference of 3 °C, generated a command signal (ord) of T_p in the output. This command signal (ord) could be input to the heat exchanger, which heat unless at least 3 °C to reach 41 °C.

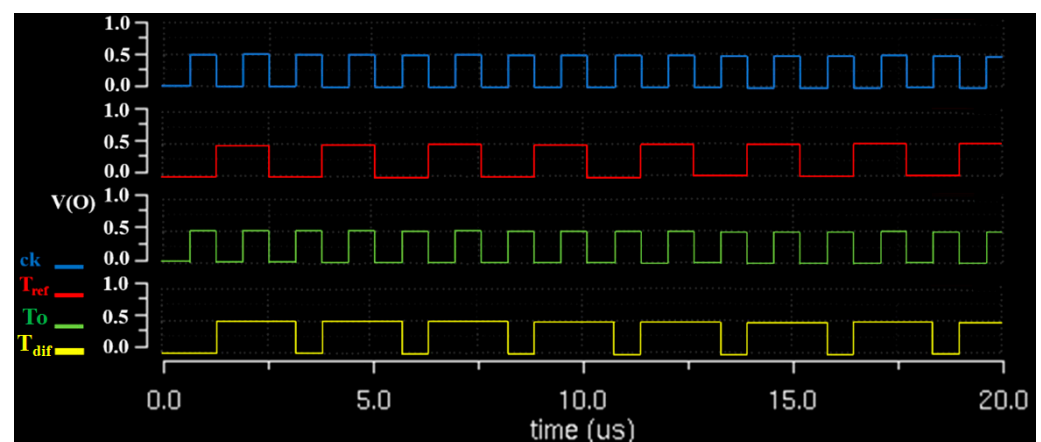


Figure 10. Measurement results for the pulse signal corresponding to temperature.

It can be noted that T_a , T_p , T_s , and T_x were accurately output when the pulse waveform signals corresponding to 41 and 43 °C were periodically generated in T_{ref} . When T_{ref} and T_o were compared in the D-flip flop, the signal generated from T_{dif} could minimize the delay signal (T_1 and T_2), as shown in Figure 11. Therefore, the signal ($T_{(t)}$) generated from T_{dif} could generate an accurate signal without an error, as shown in Equation (3) [25].

$$T(t) = \frac{(T_2 + T_1)}{T_r} - (1 - e^{-dt}) \quad (3)$$

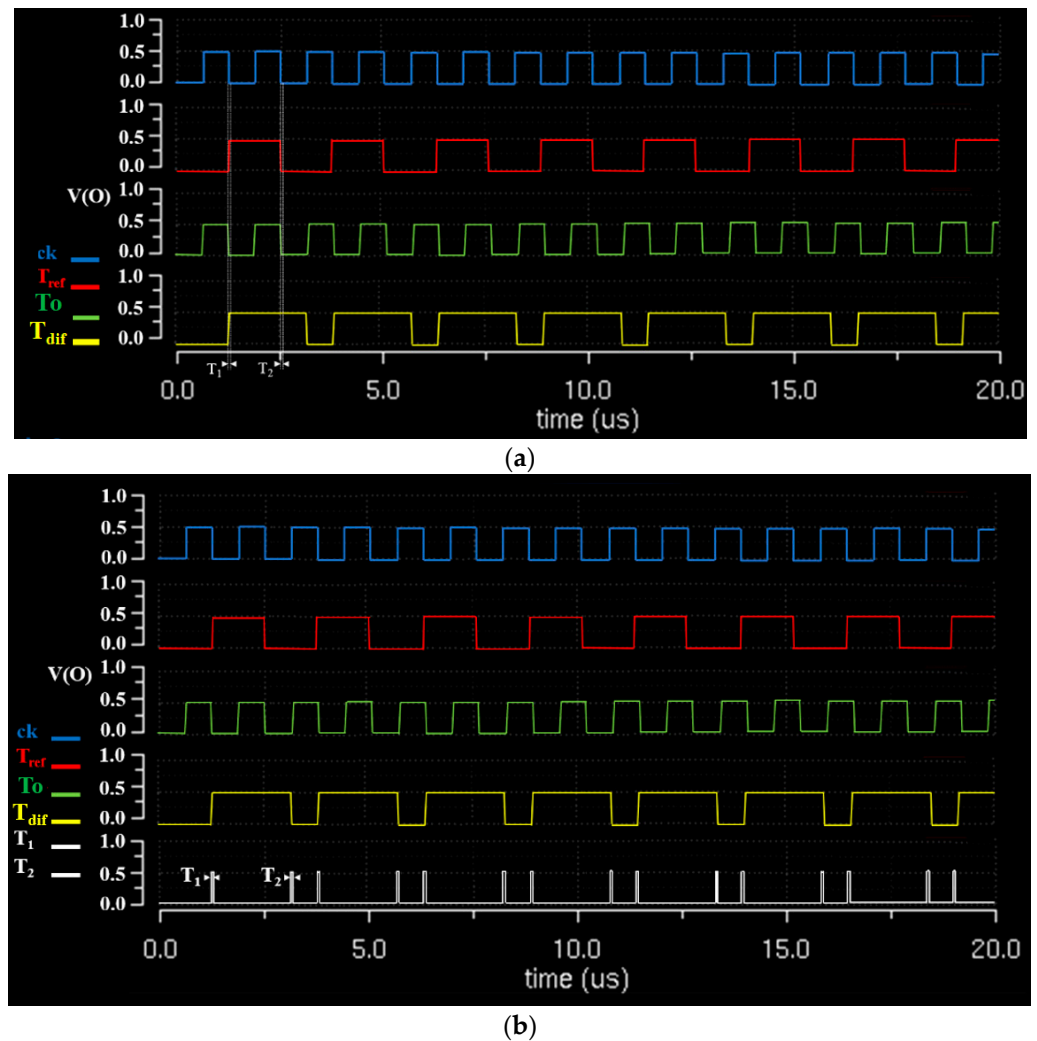


Figure 11. Measurement results of the pulse signal with response delay in parallel with the temperature comparison and decision (T_{dif}). (a) Response delay; (b) Sampling of response delay.

Here, $T_{(t)}$ represents the period of the delay signal for the difference between T_1 and T_2 , and T_r represents the theoretical minimum delay time. As shown in Figure 11, T_1 and T_2 generated 209 ns each, and T_r generated 4.18 ps. Moreover, the error for the delay time of the module was within 1.8%. Therefore, the accuracy, reliability, and reproducibility of the module's operation had a high level of 98.2%, respectively.

The control performance (inflow, outflow, and feedback) was tested by connecting the designed module to a beaker. Figure 12a presents an image that was obtained using a thermal imaging camera for the thermal temperature state of normal saline inside the beaker. We also evaluated the correctness of signals T_a , T_p , T_s , and T_x obtained from the LUT through thermal imaging, confirming that the temperature of the drug was maintained in the therapeutic range by the system. Additionally, the thermal temperature distribution

signal for the thermal temperature control performance according to the pulse waveform is shown in Figure 12b,c. The results show that, over time, the heat temperature control of the heat exchanger was well-adjusted so that it could be properly maintained.

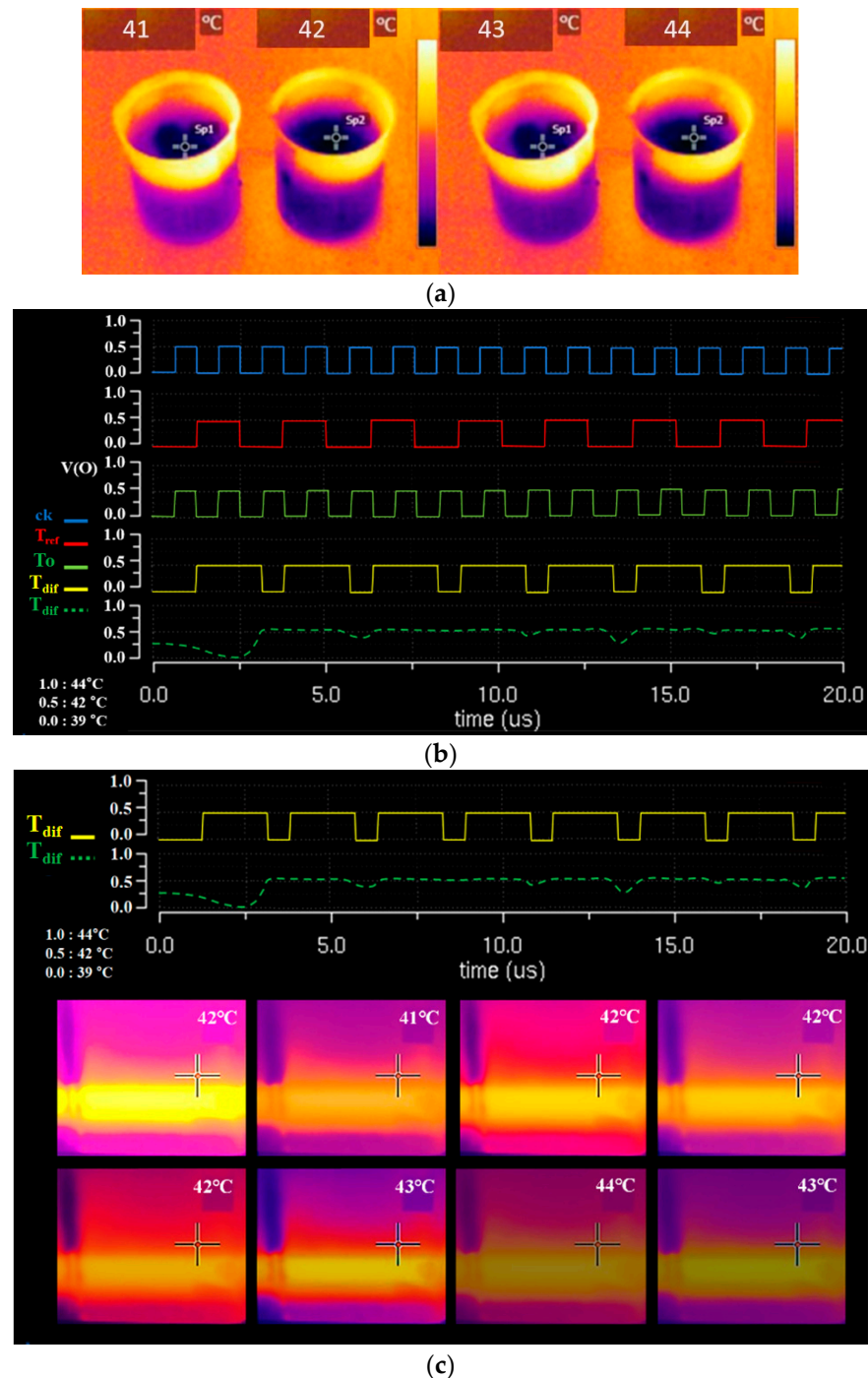


Figure 12. Comparison for measured output pulse signal, thermal condition graph, and thermal imaging camera. (a) Shooting of thermal imaging (high temperature of normal saline); (b) Pulse signal and thermal condition graph; (c) Pulse signal and thermal imaging camera.

When the T_{dif} signal was generated from the TC, the LUT provided T_a , T_p , T_s , and T_x signals to control the temperature of the heat exchanger (shown in Figure 13) and supply constant heat from the heat exchanger during time changes. By performing the interlocking function of TC and LUT, the heat distribution graph showed that the control system

maintained its temperature within the desired range. Therefore, this result confirmed that the operation was suitable for HIPEC's surgical treatment.

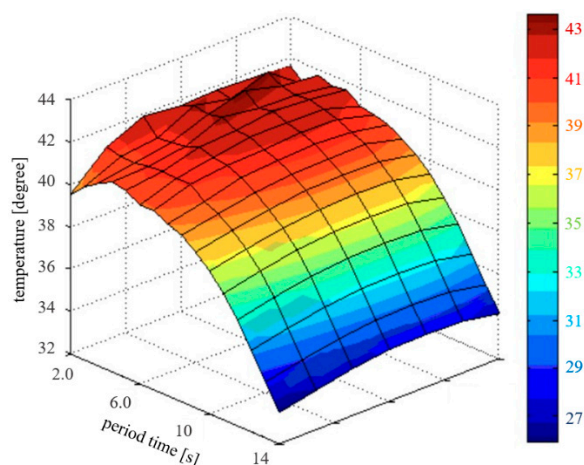


Figure 13. Three-dimensional (3D) graph based on experimental results verifying that the temperature was maintained.

Finally, Figure 14 shows the connected circuits that were configured to verify the proposed design method for the three-dimensional (3D) printer, the PCB (printed circuit board) board, and the motor, and evaluates whether the temperature was controlled using a temperature sensor, monitor device, and thermal imaging camera. For the operation of the evaluation, the supplementary version of this discussion can be referred to, and when the temperature fell below 41 °C (T_p) in the equipment, the control system automatically raised the heat to reach the range of 41–43 °C (T_s). If the heat reached between 44 °C and 46 °C (T_a), the control system automatically stopped the operation (T_x) and then adjusted to stay at 41 °C to 43 °C (T_s). Therefore, the measurement results were consistent with the experimental (see Figure 13) and simulation results (see Figures 7–13). When operating for 120 min in the control system so that the temperature could reach a stable temperature (T_s) at a range between 41 °C and 43 °C [15,21–24] and a heat temperature of 42 °C after 5 min in the temperature meter. This was measured, and after 50 min, a 43 °C measurement result was obtained from the thermal imaging camera. When considering the operation time of 120 min [15,21–24], the measurement results were analyzed to be controllable in a sufficiently stable state.

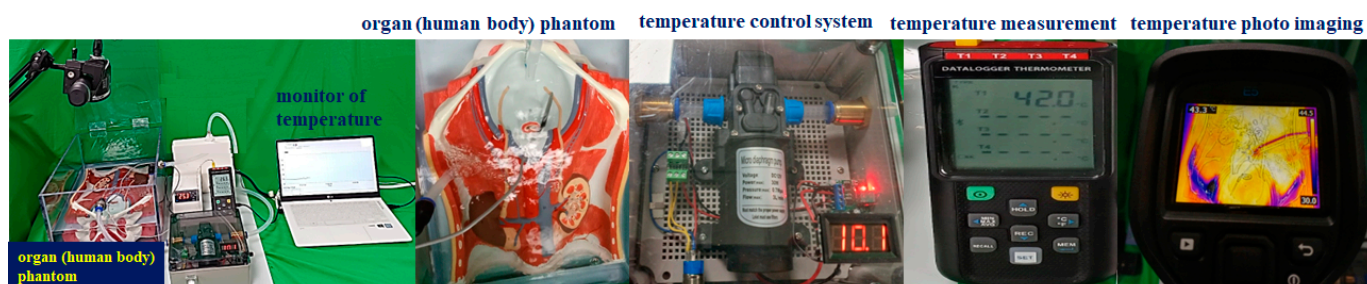


Figure 14. Proposed system fabrication and temperature test.

4. Discussion

In current surgical procedures, the HIPEC treatment method manually controls the temperature with an assistant. If the heat rises, it starts to lower the heat; if the heat decreases, the assistant manually adjusts to increase the heat. In addition, if the fever is constant, the system is on standby; if the fever starts to decrease or increase, the treatment has to stop until the proper temperature is maintained. Therefore, the treatment process is cumbersome and time-consuming. However, this study has the advantage of automatically

adjusting the heat through temperature monitoring to solve the complicated process. When comparing and judging temperatures and transmitting the provided data to the LUT to generate a command signal, the reaction speed was the crucial parameter. As the reaction speed increased, the operational error decreased. Moreover, the reaction speed is an essential factor because it is related to the accuracy and reliability of the system. In this regard, the proposed system has a high response speed and high reliability. The designed system can also be evaluated by experimenting with animals. However, our experiment of the designed system focused on maintaining the heat in the heat exchanger (41–43 °C) and evaluating the accuracy and reliability of the compensation function through comparison, judgment, LUT data learning, and the generation of a light signal by sensing heat. Note that evaluating the accuracy and reliability of the compensation function is paramount. More specifically, when the temperature is too low or too high, the pulse signal conversion timing for the comparison and discrimination to reach the treatment temperature range (41–43 °C) through the TC control is considered to be very important. The reason for this is that the comparison and judgment speed for the control can be related to the performance of TC's control speed. Therefore, the fast operation of the heat exchanger by sending a command signal (*ord*) to the LUT through a quick comparison and judgment of the TC is related to the operation time. The operation time was 90–120 min in total, and during that time, it was very important to reduce the delay time of the signal response characteristics to increase the patient's treatment performance through rapid control and circulation. Thus, the experiments and functional tests used a beaker and a thermal imaging camera, which were considered appropriate methods to evaluate the proposed system. Nevertheless, animal experiments are necessary for commercialization in the future. As shown in Table 2, the proposed method is estimated to be 51 times faster than previously studied methods, considering the system response speed. The data for the comparison and judgment obtained in this study included binary signals detecting heat. The cases studied in Table 2 are modules designed for error correction through comparison, judgment, and feedback on binary signals rather than a system for thermal treatment. Consequently, the important part of these modules was the response speed of the signal. Hence, improving the response speed is significant for comparison and judgment. In Table 2, the response speed of the proposed system outperforms that of the response speed in the existing literature. As shown in Figure 11, T_1 and T_2 generated 209 ns each, and T_r generated 4.18 ps. The reason for this is that T_1 and T_2 should be theoretically reached within 1 μ s ($T_r = 1 \mu$ s), but according to cases announced in 2021, their delay time was within 225 ns to 73 μ s. Thus, the smaller the delay time, the better the module's performance, allowing it to become superior [26–31]. In particular, the error for the delay time of the module was 1.8% compared to the delay time in [26], which could reach the 98.2% level for the accuracy, reliability, and reproducibility of the module [32,33].

Table 2. Comparison of response time difference for proposed and existing systems.

Reference	Response Speed [μ s]	Response Speed Difference [μ s]	Performance Difference [times]
[26]	0.225	0.016	1.08
[27]	73.1	72.891	349
[28]	12.8	12.591	60.8
[29]	5.00	4.791	23.0
[30]	30.0	29.791	143
[31]	8.00	7.791	37.3
this work	0.209	—	—

5. Conclusions

In this paper, a control system was proposed to maintain and compensate the treatment temperature in HIPEC surgery using high-temperature drugs for ovarian cancer surgery.

The small tumor tissue remaining after ovarian cancer surgery is difficult to treat surgically. Therefore, the method proposed in this study can increase the therapeutic effect of hyperthermia chemotherapy by injecting and circulating the drug in the abdominal cavity and keeping the treatment temperature constant. In addition, by preventing the temperature from rising above a certain point, it can reduce the side effects caused by damage to normal tissues.

During the treatment, the temperature of the medicinal substances should always be constant; however, the fever may be lowered because the drug circulates through and outside the body. Conversely, heat may increase. Therefore, if the heat is manually controlled by monitoring the temperature from the outside, this process has the disadvantage of interfering with the treatment. However, the advantage of our study is that the heat can be automatically reduced through external monitoring. Alternatively, the heat can be automatically increased. Additionally, the proposed system can retain heat and has an automatic control function. The method for maintaining/compensating for the temperature through heat comparison/determination, data collection/learning of the LUT, and the control signal output is considered a crucial and groundbreaking technology. Further, the response time for the proper control and comparison, and judgment of heat was substantially short in the feedback process because the time required for comparison and judgment was minimal. Moreover, the system had a low margin of error (within 1.8%) and high accuracy (98.2%). The application of this technology can eliminate errors in manual methods controlled by humans and guarantee accurate, safe treatment and rapid surgery. In conclusion, the proposed system has good application prospects and could be applied to the field of surgery, obstetrics, and gynecology.

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