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Disclosure of the significant thermal effects of large blood vessels during cryosurgery through infrared temperature mapping

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Abstract

During cryosurgery the large blood vessels entering the frozen volume can be an important source of temperature non-uniformity and possible under-dosage for the target tissues. In this study, the thermal effects of large vessels during cryosurgery were experimentally investigated by introducing infrared thermography system on monitoring both simulated and animal experiments. For all experiments, the freezing was supplied by a 5 mm diameter cryoprobe with liquid nitrogen running through. Tissue temperature responses during freezing and thawing were recorded by an infrared thermography system. It was demonstrated that for different geometrical configurations between the simulated vessels and the positioning of the cryoprobe, a very different temperature profile will be induced even under the same freezing. The results for the cases with single vessel and with count-current vessel pairs indicated that different vascular models produce significantly different temperature responses for a given freezing pattern. Both the simulated and animal experiments suggested that the heating nature of the flowing blood in the large vessels can produce steep temperature gradients and inadequate cooling to the frozen tissues, and therefore may seriously contribute to failed-killing of tumor during cryosurgery. The physical pictures disclosed in this paper may help planning more successful cryosurgery in the near future.

Keywords: Cryosurgery; Large blood vessel; Infrared thermography; Temperature mapping; Thermal effect; Bioheat transfer; Tissue vasculature

1. Introduction

Blood flow through large vessel ($\geqslant$0.5 mm in diameter, also termed as thermally significant vessel) plays an important role in the temperature responses of biological tissues subject to either heating or freezing [1,2]. It has long been known that both heating and freezing of in vivo tissues have important applications in tumor treatment. The modality of in vivo freezing tissue is usually referred to as cryosurgery, while the heating method can be used as tumor hyperthermia. Currently, cryosurgery and hyperthermia have been used in the treatment for almost all types of tumors [3,4]. Due to its important applications in tumor hyperthermia and cryosurgery, the study on thermal behavior of large blood vessels had ever been a focus in the bioheat transfer field. Up to now, many vascular heat transfer models exist, which account for the convective effects of large blood vessels on the temperatures of tissues. However, most of them were developed mainly for hyperthermia purpose [1,5–7]. In cryosurgery, the large blood vessels' contribution to the heat transfer in living tissues subject to freezing has received few attentions [2,8]. In fact, blood flow through large blood vessel also plays an extremely important role in the temperature responses of the biological tissues during cryosurgery.

Anatomically, tumors are usually highly perfused tissues, which are often situated close to or embedded with large blood vessels, since tumor's quick growth and survival ultimately depend on its blood vessel network. Due to the presence of large blood vessel, the blood flow inside large vessel in fact represents a source to heat the nearby frozen tissues and thereby limit freezing lesions during cryosurgery. Under this condition, part of tumor cells will survive after cryosurgery, which would lead to high recurrence rates of tumor. More specifically, tumor cell survival close to large blood vessels is often correlated with tumor recurrence after treatment [9]. The heating effects of large

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blood vessels and vascular perfusion during cryosurgery can be minimized by vascular exclusion, in which vascular inflow occlusion is performed by clamping the entrance of the large vessels [10]. However, the vascular exclusion requires a major surgical procedure, which negates one of the major advantages of cryosurgery—the use in a minimally invasive manner (percutaneous or laporoscopic). In addition, cutting off circulation of large blood vessels or bleeding due to ruptures of some key vessels by the iceball during the cryosurgical procedure may result in undesired injury to downstream healthy tissues or organs [8]. Moreover, there is still concern about the freezing injury during cryosurgery to major vessels in a young patient with anticipated subsequent growth [11], although blood vessels do seem to tolerate some extent of freezing [12].

Based on the above consideration, in order to perform a successful cryosurgery for the case with large blood vessels embedded in or close to the tumor, it is very necessary to fully understand the effects of large vessels on the detailed temperature responses of tissues subject to controlled freezing. In our previous work [8], we had investigated such thermal behavior of large blood vessels through numerical simulation, and obtained some significant conclusions. Since there are many factors affecting the tissue temperature in the actual process, it should be extremely essential to conduct the corresponding experimental investigation of the thermal effect of large vessels. Currently, a thorough investigation on this issue is highly desirable. Zhang et al. [2] may make the first attempt to perform a simulating experiment as well as to develop a theoretical model for the cryogenic heat transfer in simulated tissues embedded with large blood vessels. They used a copper block with a flat and circular surface frozen by liquid nitrogen as cryoprobe to freeze the tissue phantom embedded with two parallel counter-current Teflon tubes. The influences of the blood vessel entrance temperature, the vessel diameter, and the blood flow velocity to the tissue temperature distributions were investigated respectively. Two years later, Massalha et al. [13] presented a repeated similar experiment. However, both experiments applied a copper block with a flat and circular surface frozen by liquid nitrogen as cryoprobe. Such simplification is much different from the condition of cryoprobe in a real large-vessel-involved cryosurgical treatment. In addition, both the above experimental works adopted the thermocouples as temperature sensor to measure the temperature responses of tissues. Although local monitoring technique using thermocouples is valuable and has contributed significantly to cryosurgery, it has two evident drawbacks. First, the procedure is invasive and requires the insertion of thermocouples into the tissue. Second, the information produced by local monitoring is restricted only to the measured site. However, during cryosurgery, it is important to precisely monitor and evaluate the extent of freezing. Failure to evaluate correctly the extent of freezing can lead to either insufficient or excessive freezing and consequently, to tumor recurrence or to destruction of healthy tissue [3]. This problem was not resolved with local monitoring of cryosurgery. Infrared thermography has been investigated as a means of visualizing the region frozen during cryosurgery [14]. It is a promising technique because the sensitivity level can be adjusted to the operator information about a particular temperature band, and it can record an isotherm of lethal freezing temperature that gives the surgeon more relevant information about the destroyed volume than a localized measurement of temperatures by thermocouples. In addition, infrared thermography has the advantage of noninvasive, risk-free, cost-effective, and easy to perform.

In this study, infrared thermography was introduced to experimentally disclose the thermal effect of large blood vessel during cryosurgery. To present the heating nature of large blood vessel in an actual cryosurgery, the cooling power was supplied by a 5 mm diameter cryoprobe with liquid nitrogen running through. In addition, different from the thermocouples, infrared thermography has the advantages of non-contact, high spatial resolution and quickly obtaining image of temperature distribution. For comparison, both simulated and animal experiments were conducted. The simulated experiments were respectively performed in a tissue phantom and an in vitro tissue. The animal experiments were performed on rabbit ear and rabbit stomach respectively.

2. Material and methods

The HR-II Medical Infrared Imaging System (made by the Institute of Optics and Electronics of North China, Beijing) was used to map the transient temperature distribution in the present experiment. This infrared thermographic equipment has a discrimination of 0.1 °C at ambient temperatures and 0.5 °C down to −40 °C, which represents the lower limit of the equipment, and the spatial resolution is better than 2 mini-radians. This remote infrared thermographic camera can be accurately focused from a wide range of distances. During experiments, the infrared camera was placed on the front of object to be tested, and the vertical distance between the camera and the object was about 80 cm. The automatic focus lens embedded inside the camera can guarantee the quality of the image. A liquid nitrogen based cryosurgical system [15] (developed by the Technical Institute of Physics and Chemistry, Chinese Academy of Sciences) was applied to supply the cooling power, in which a 5 mm diameter cryoprobe was particularly selected to perform the simulated cryosurgery.

As is well known, the blood flow inside large vessel usually plays a significant role of heat source or heat sink in the heat transfer of tissues. When superficial large vessels have some pathological changes, the corresponding changes in its thermal effects can reflect to the temperature distribution at skin surface. Based on this principle, the infrared thermographic system has been widely used in the diagnosis of some vascular diseases [16–21]. Considering this feature of infrared thermographic system, we will attempt to use it to study the thermal effects of large blood vessels in the cryosurgical procedure.

2.1. Phantom study

The medium used to simulate the tissue was semitransparent gel phantom composed of 10 percent of gelatin and 90 percent of water in weight. A 2 mm OD/1.6 mm ID Teflon tube was used to simulate the large blood vessel. The tissue phantom was

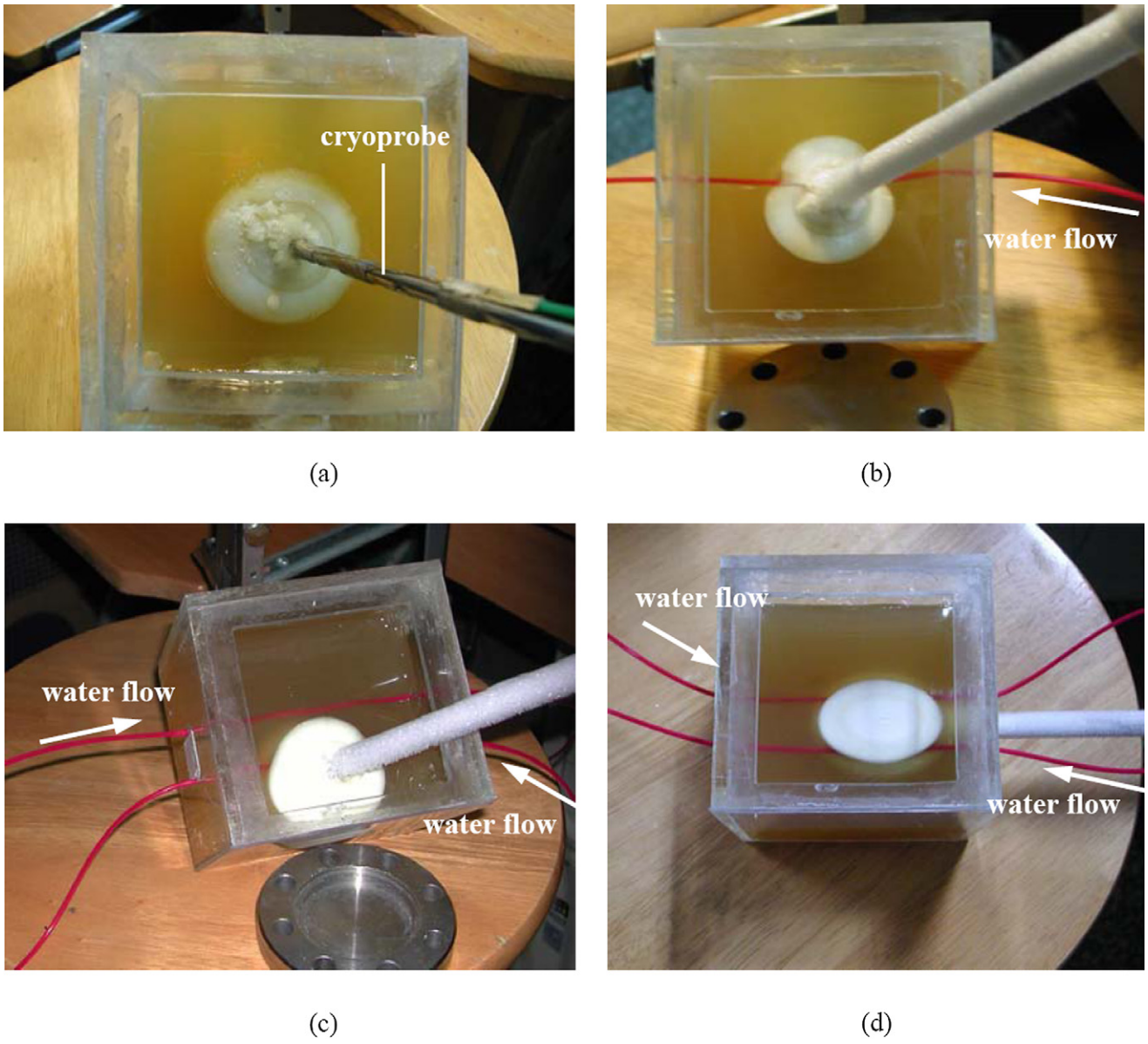

Fig. 1. Snapshot of experimental setup of tissue phantom, in which (a) is for the case with no large blood vessel, (b) is for the case with a single large blood vessel, (c) is for the case with parallel counter-current vessel pairs (in which the cryoprobe is vertical to the simulated vessel), and (d) is for the case with parallel counter-current vessel pairs (in which the cryoprobe is parallel to the simulated vessel).

formed and contained in a cubical organic glass box, with each outer side length of 10 cm and thickness of 0.5 cm. The Teflon tube passed through the 2-mm-diameter holes drilled on the two opposite boards of the organic glass box, and the depth of simulated blood vessel was 5 mm after the tissue phantom solidified in the box.

In experiments, the water was used to simulate the blood. Water came from an isothermal water bath. In order to prevent the melting of phantom, the water temperature was controlled at about 25 °C. The circuit pressure used to drive the water flow was achieved through a peristaltic pump. In such way, the pulsatile characteristic of blood flow was well simulated. The flow velocity or flux of water can be conveniently adjusted by changing the rotate speed of peristaltic pump. In this study, the mass flow flux of water was assigned as 30 g/min.

Four different cases were investigated for the simulated experiments with tissue phantom, which were the case with no large blood vessel, the case with single large blood vessel, the case with parallel counter-current vessel pairs (in which the cryoprobe was vertical to the simulated vessel), and the case with parallel counter-current vessel pairs (in which the cryoprobe was parallel to the simulated vessel), respectively. The snapshots of the above experimental setups were shown in Fig. 1. For the case with single large blood vessel, the distance between cryoprobe and blood vessel was 5 mm. For the case with parallel counter-current vessel pairs, the distance between the parallel vessels was 20 mm. The process of making the counter-current vessels was as follows: first, the Teflon tube was guided through the 2-mm-diameter holes drilled on the two opposite boards; then it was swerved at the outside of the box; after

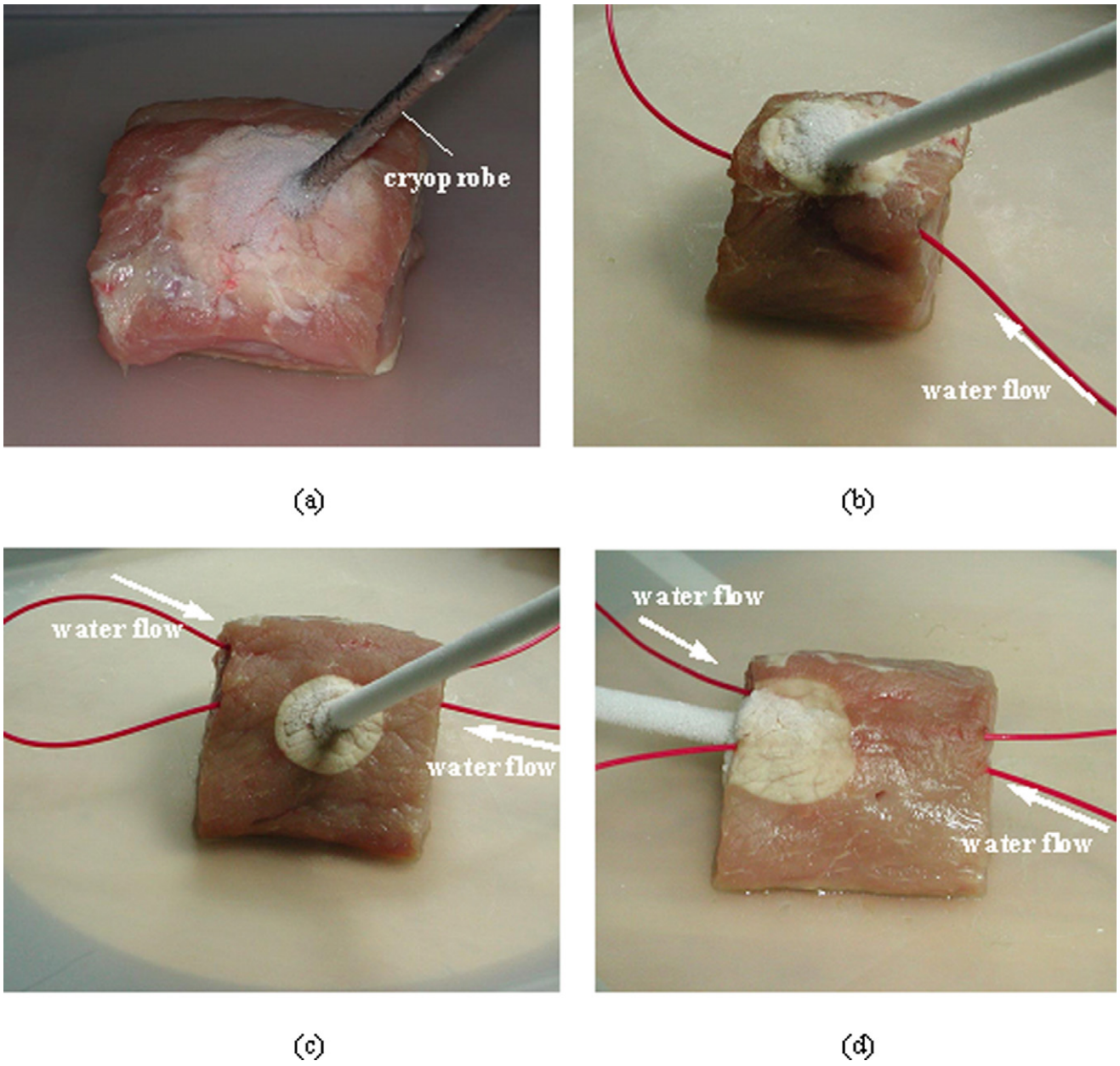

Fig. 2. Snapshot of experimental setup of in vitro tissue, in which (a) is for the case with no large blood vessel, (b) is for the case with a single large blood vessel, (c) is for the case with parallel counter-current vessel pairs (in which the cryoprobe is vertical to the simulated vessel), and (d) is for the case with parallel counter-current vessel pairs (in which the cryoprobe is parallel to the simulated vessel).

that, it was guided through another two holes with the same sizes, which were 20 mm apart from the former holes. The distance between cryoprobe and the near vessel was 5 mm when the cryoprobe was vertical to the simulated vessel. The distance between cryoprobe and the surface formed by the parallel vessel pairs was 10 mm when the cryoprobe was parallel to the simulated vessel.

2.2. *In vitro tissue study*

Although tissue phantom has the thermal properties similar to biological tissue, it does differ from the real biological tissue, and it is hard to simulate the other properties of biological tissue such as anisotropy. In order to simulate more really the thermal effect of large blood vessel embedded in biological tissue, similar simulated experiments inside in vitro tissue were also performed.

Muscle pork was selected as experimental material. The large blood vessel was also simulated by a 2 mm OD/1.6 mm ID Teflon tube. The water temperature at the inlet of Teflon tube was maintained at about 37 °C in order to simulate the real blood flow condition in human body. Other setups were taken the same as that in the phantom experiments.

Four cases were investigated for the simulated experiments with in vitro tissue, which respectively corresponded to that for the phantom experiments. The snapshots of the experimental setups were shown in Fig. 2. For the case with single

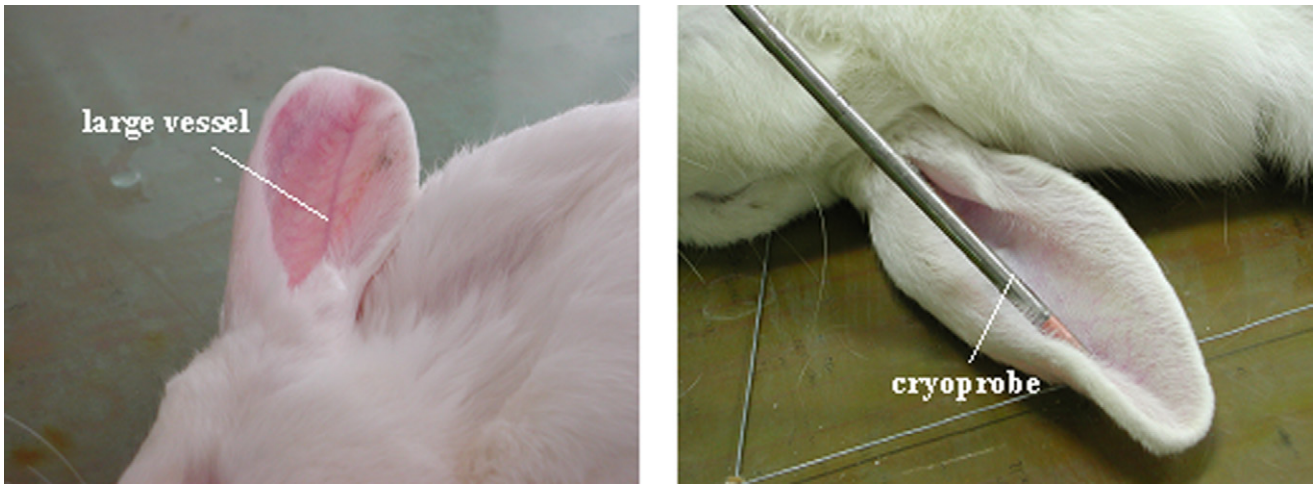

Fig. 3. Snapshot of rabbit ear before and during cryosurgery.

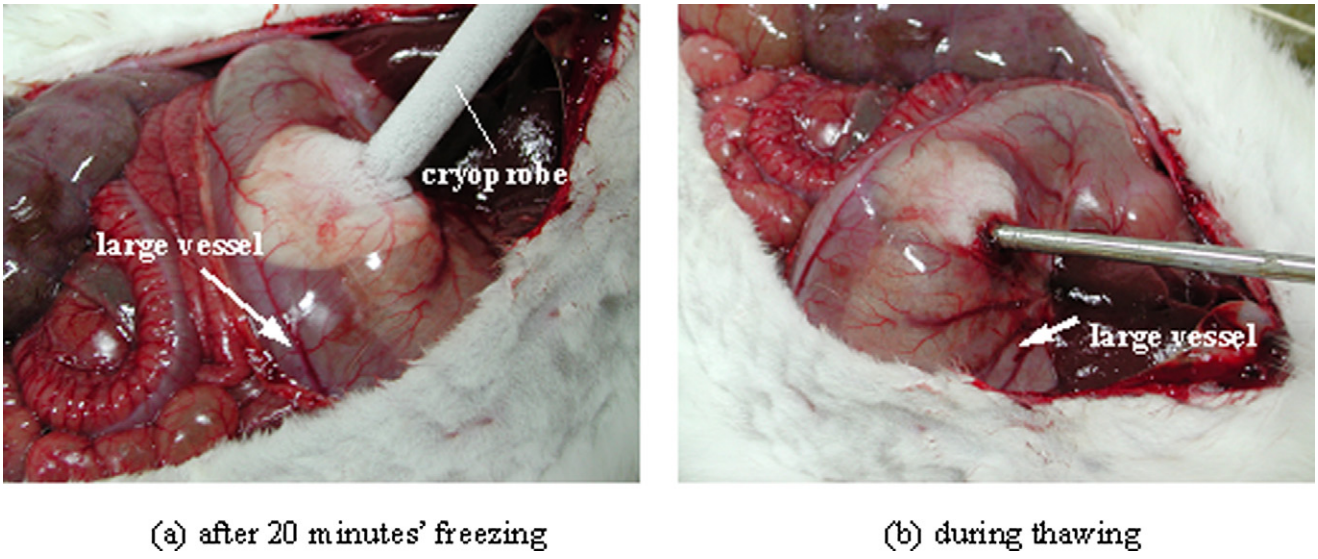

Fig. 4. Snapshot of rabbit stomach during cryosurgery.

large blood vessel, the distance between cryoprobe and blood vessel was about 5 mm. For the case with parallel countercurrent vessel pairs, the distance between the parallel vessels was about 10 mm. The distance between cryoprobe and the near vessel was about 5 mm when the cryoprobe was vertical to the simulated vessel. The distance between cryoprobe and the surface formed by the parallel vessel pairs was about 10 mm when the cryoprobe was parallel to the simulated vessel.

2.3. Animal study

The merit of the above simulated experiments lies in that it can pre-position the simulated large vessels as desired, and then clearly exhibit the thermal effect of large vessel. However, due to the complexity of biological body, the phenomena observed in simulated experiments may deviate from that in a real cryosurgery to some extent. In order to reveal more really the thermal effect of large vessel during a practical cryosurgery, animal experiments were also performed in this study. The experiment object was a 2 kg weight New Zealand white rabbit. Before the experiment, the rabbit was anesthetized with ethyl carbamate (1 g/kg intraperitoneal). After that, the rabbit was fixed on an operating table.

Two perfusion-rich organs (rabbit ear and stomach) were specifically chosen to perform freezing experiments, where the blood vessels are visible with the naked eye. The snapshots of rabbit ear before and during cryosurgery were shown in Fig. 3, and the snapshots of stomach during cryosurgery were given in Fig. 4. The superficial large blood vessels distributed at rabbit ear and stomach can be clearly seen from Figs. 3 and 4. In order to obtain clear infrared thermographs, the rabbit's bowels were not covered with medical pledget, as shown in Fig. 4.

The freezing experiment was first performed on the surface of rabbit's right ear, in which the freezing time was 5 min, then stopping freezing and thawing spontaneously at room temperature. During cryosurgical procedure, the infrared thermographs

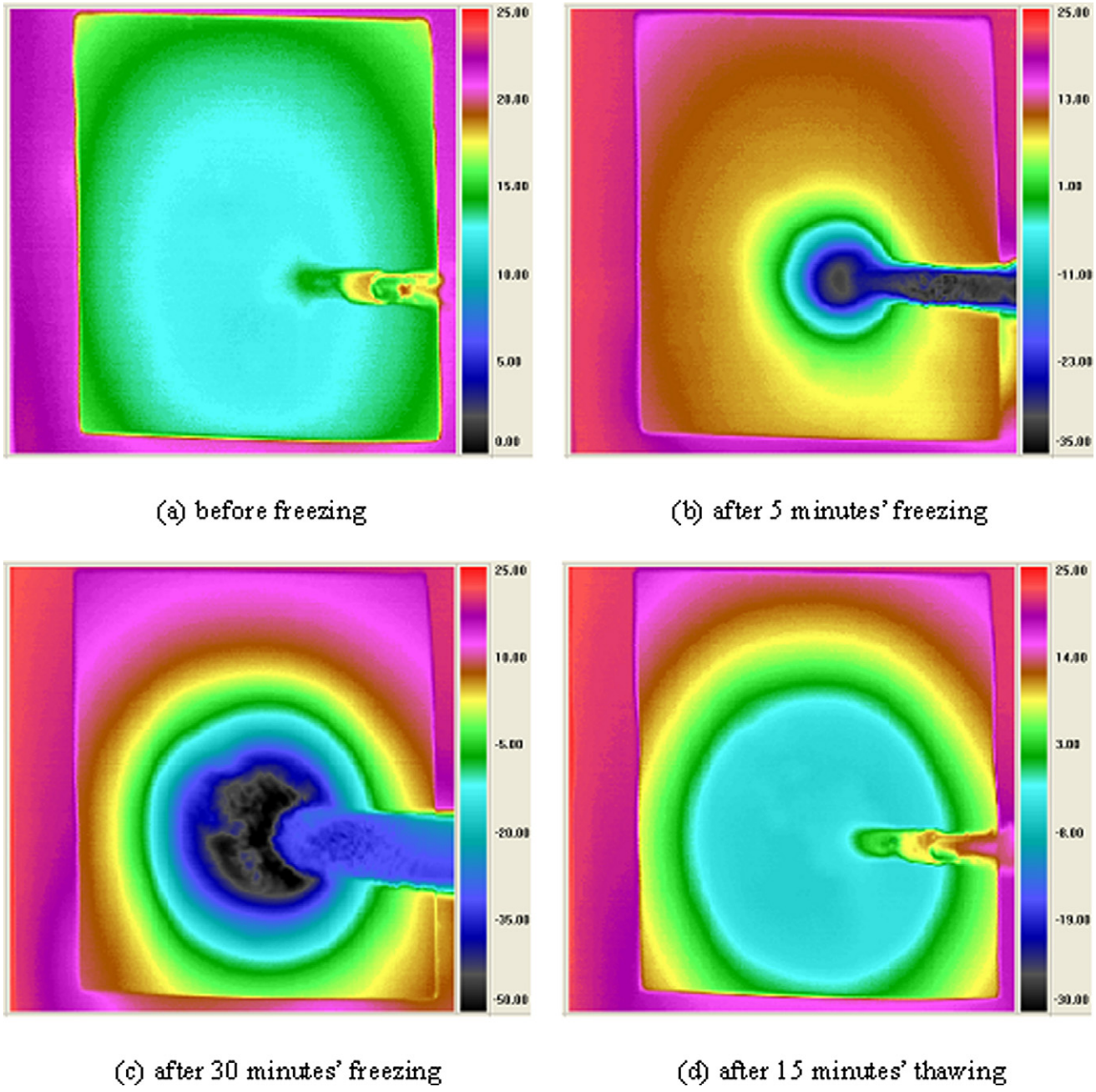

Fig. 5. Infrared thermographs for the case of no large blood vessel (phantom experiments).

of rabbit ear were recorded in computer. After cryosurgical experiment at rabbit ear, the freezing experiment was then performed on rabbit stomach, and the detailed process was as follows: first, using the medical scalpel to open rabbit's abdominal cavity; second, inserting the cryoprobe into its stomach at the position close to large blood vessels; then start the cryosurgical system to freeze the target area, and recording the infrared thermographs at the surface of stomach. The total freezing time was 20 minutes, then stopping freezing and thawing spontaneously at room temperature. The rabbit was sacrificed after cryosurgical experiment on the stomach, by injecting over-dosage anesthetic into its heart.

3. Results

3.1. Phantom experiments

Before experiments, the infrared thermographic system has been correlated using a mixture of ice and water. The reason for not using multiple temperature probes to correlate in situ the infrared zones is that the temperature probes will evidently affect the results obtained from infrared system. The experimental results are shown from Fig. 5 to Fig. 8. As illustration, only parts of representative infrared thermographs are given. In these figures, different colors denote different temperature range, from which the boundaries of iceball and necrosis region of tissues

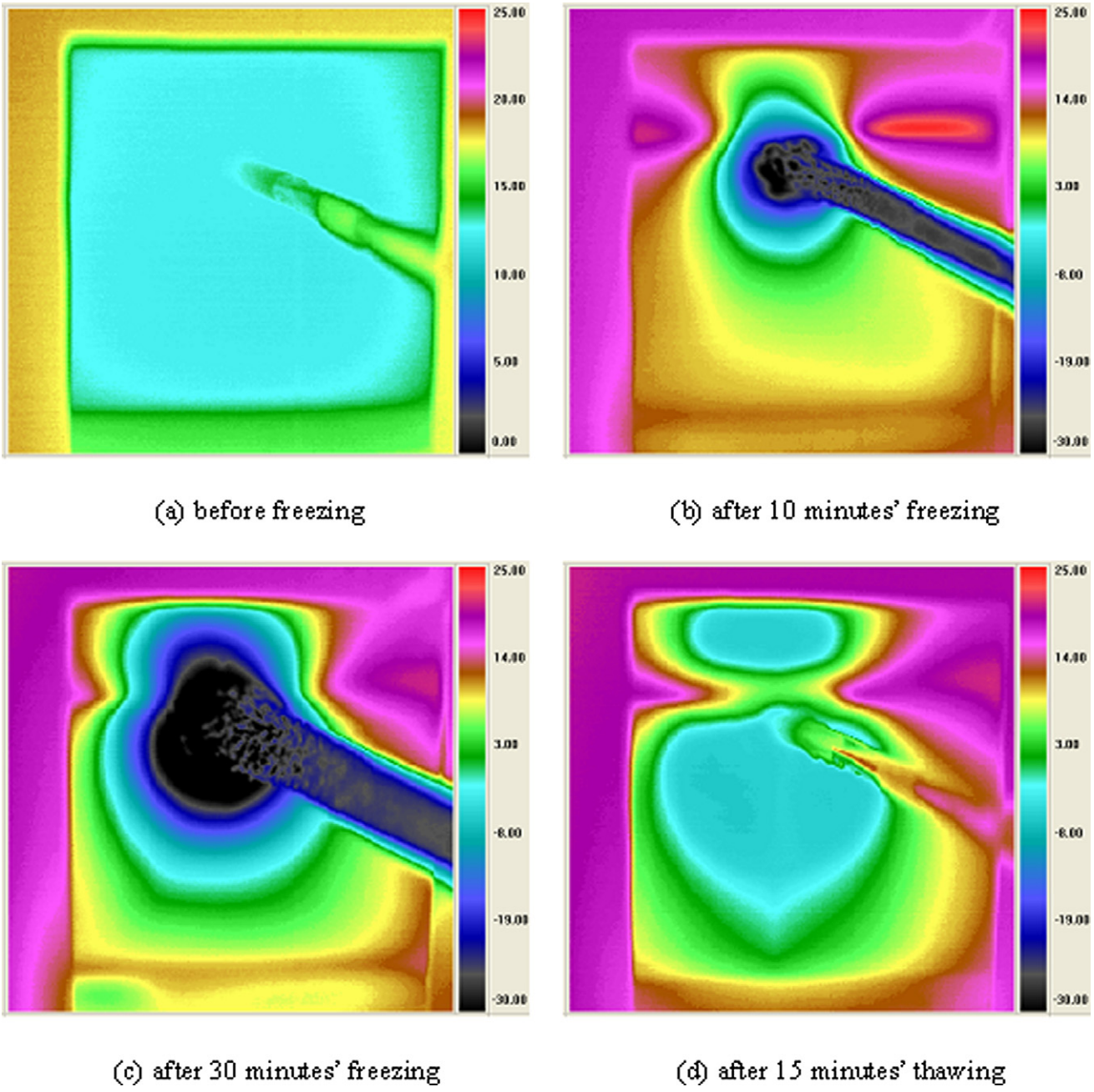

Fig. 6. Infrared thermographs for the case with single large blood vessel (phantom experiments).

can be easily discriminated. It is clearly shown in Fig. 5 that for the case of no large blood vessel, the temperature distribution of tissue phantom appears relatively symmetrical, and the isotherm at the surface of phantom basically distributes as circular one centered at the surrounding of cryoprobe, and similar distribution can be found in the formation of iceball during freezing. The total freezing time is 30 minutes, then stopping freezing and thawing spontaneously at room temperature. The maximum diameter of iceball during freezing is about 4 cm. For the case with a single large blood vessel, due to the heat source effect of water flow, the temperature surrounding the vessel is much higher than that at other positions (as shown in Fig. 6). In addition, the tissue phantom surrounding the vessel is relatively hard to be frozen, and then resulting in that the iceball formation has the tendency of deviating from the region of large vessel. When the freezing time is long enough, the irregular-shaped iceball (which appears as concave shape nearby the large vessel, and its center deviates from the position of cryoprobe) finally enwraps the large vessel. But even at this time, the water flow in the vessel is still not frozen. During the thawing process, the phantom surrounding the vessel melts more quickly the other area.

Anatomically, the large blood vessels frequently present in the form of counter-current pairs of artery and vein. Therefore, the thermal effects of parallel counter-current vessel pairs are also investigated. Two cases are considered, in which insertion

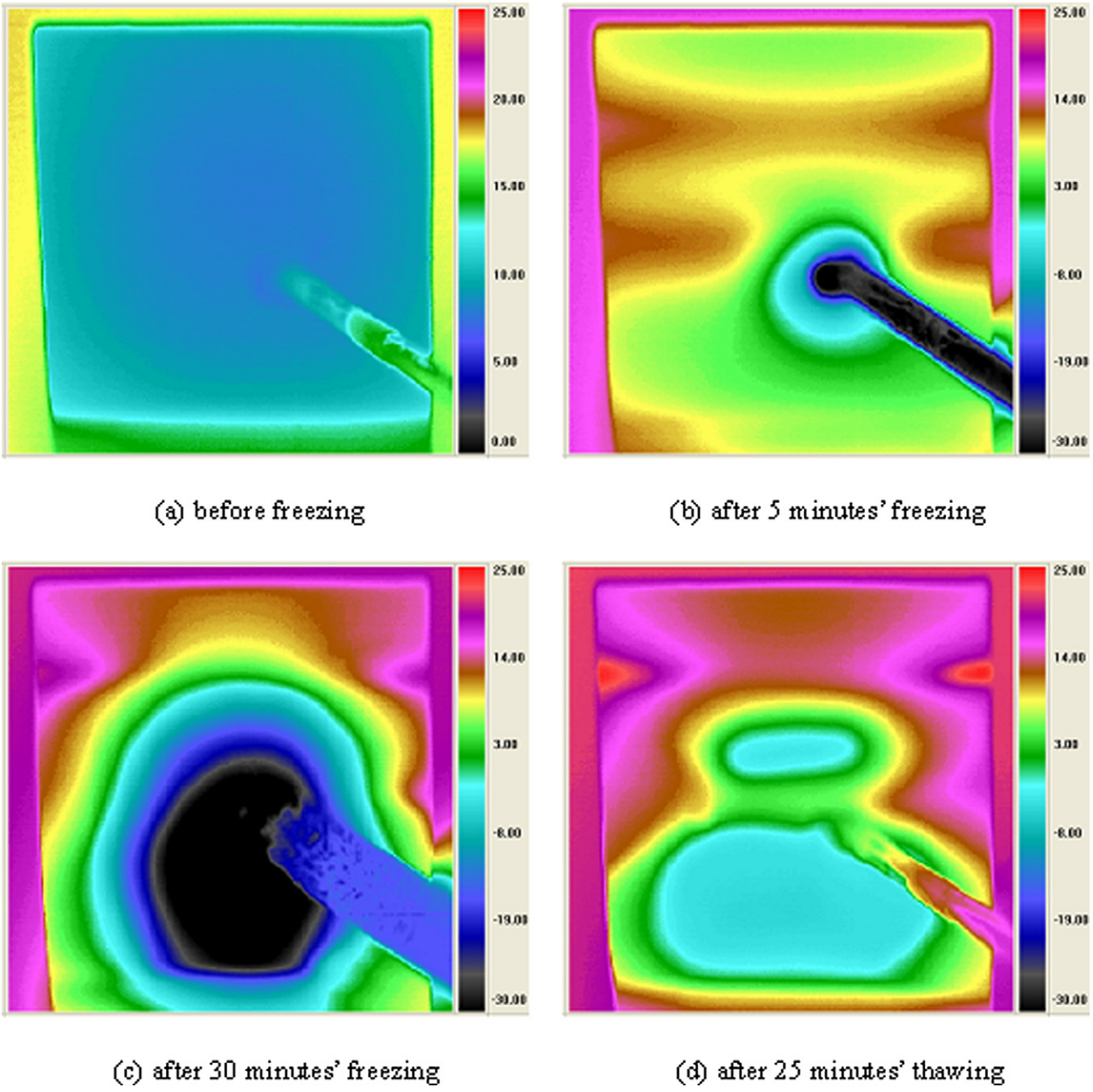

Fig. 7. Infrared thermographs for the case with parallel counter-current vessel pairs, in which the cryoprobe is vertical to the simulated vessel (phantom experiments).

of the cryoprobe is respectively vertical or parallel to the simulated vessel. The snapshot of corresponding experimental setup can be found in Fig. 1(c) and Fig. 1(d), in which the U-type Teflon tube plays both roles of artery and vein. When the water driven by the peristaltic pump flows through the cubic box at the first time, it serves as the arterial blood. When the water reflows through the box, it can be regarded as venous blood. The infrared thermographs for the above cases are shown in Fig. 7 and Fig. 8, respectively. For the vertical case, the temperature distribution of tissue phantom is remarkably different from that for the case of single large blood vessel. During freezing, the iceball formation also has the tendency of deviating from large vessel. Since the water flow in counter-current vessel pairs has provided more heat power than a single large vessel, the tissue phantom surrounding the vessel is harder to be frozen as compared with the case of single large vessel, thus the deviation of the iceball center from the position of cryoprobe is more obvious. For the parallel case, although the cryoprobe is inserted symmetrically to two blood vessels, the thermographs still appear as asymmetrical ones. The reason for this fact is that the temperature of water flow in the artery decreases at the freezing region, which results in a lower water temperature at the inlet of vein. In fact, the above results have better simulated the difference of thermal effects between artery and vein from certain degree.

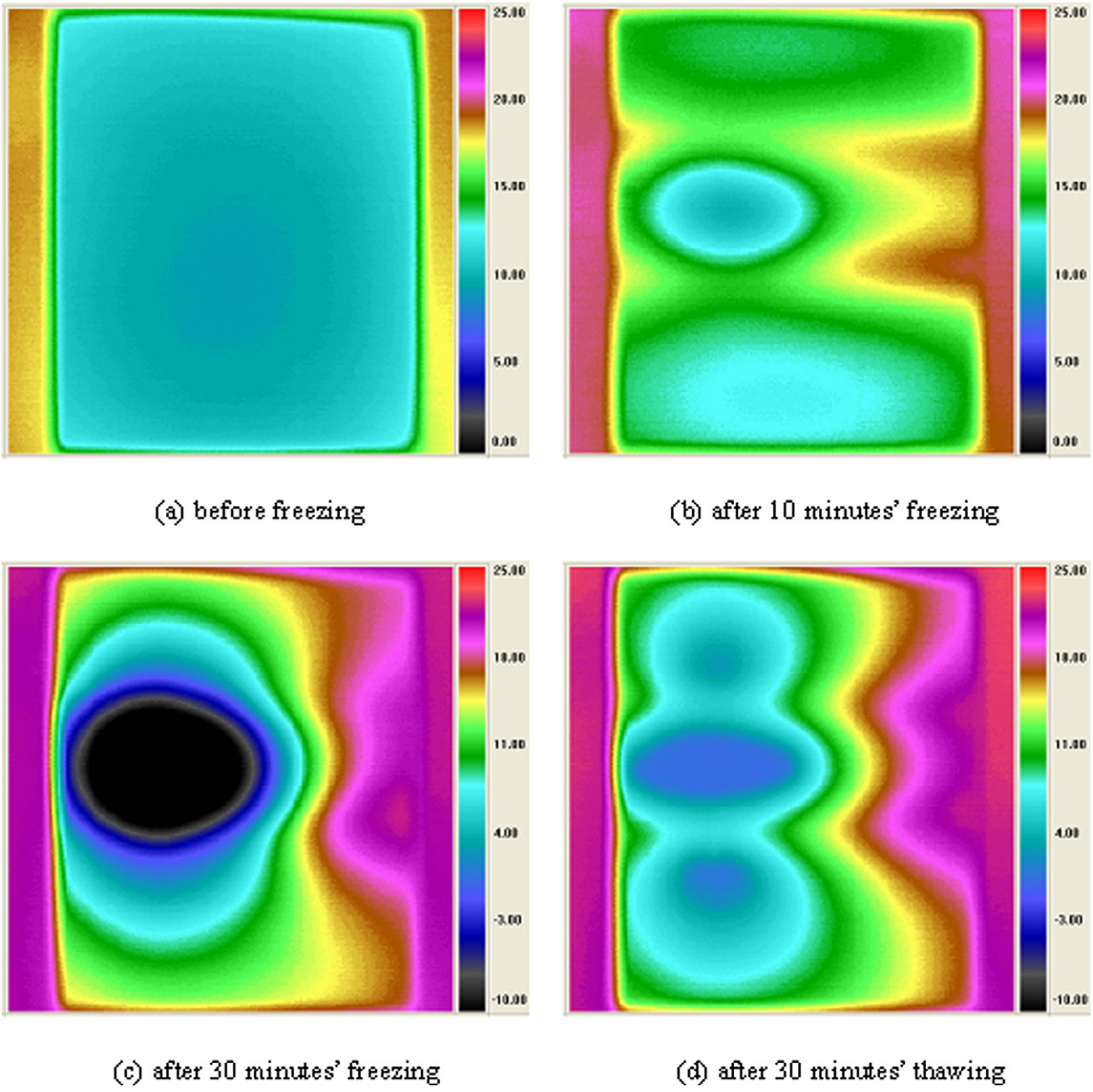

Fig. 8. Infrared thermographs for the case with parallel counter-current vessel pairs, in which the cryoprobe is parallel to the simulated vessel (phantom experiments).

3.2. *In vitro tissue experiments*

Parts of representative infrared thermographs for in vitro tissue experiments are shown from Fig. 9 to Fig. 12. For the case with large blood vessel, the results are similar to that for phantom experiments. Namely, the temperature distribution of in vitro tissue appears relatively regular, and the isotherm at the surface of tissue basically distributes as circular one centered at the surrounding of cryoprobe. For the case with large blood vessels (as shown from Fig. 10 to Fig. 12), because the temperature of water flow at the inlet is 37 °C (much higher than that in phantom experiments), the thermal effects of large blood vessels are more remarkable, and the tissue surrounding the vessel is harder to be frozen as compared with the corresponding cases for phantom experiments. In addition, it is still indicated from Fig. 10 to Fig. 12 that, although it is hard to enwrap the large vessels with the iceball, a protuberant low temperature area is produced at another side of large vessels far away from cryoprobe. This phenomenon is also resulted by the thermal effects of large vessels.

In clinics, in order to enhance the treatment efficient of cryosurgery when large vessels present at the target area, there are two possible methods: on the one hand, multiple cryoprobes should be used to produce enough freezing power to form bigger iceball enwrapping the large vessels; on the other hand,

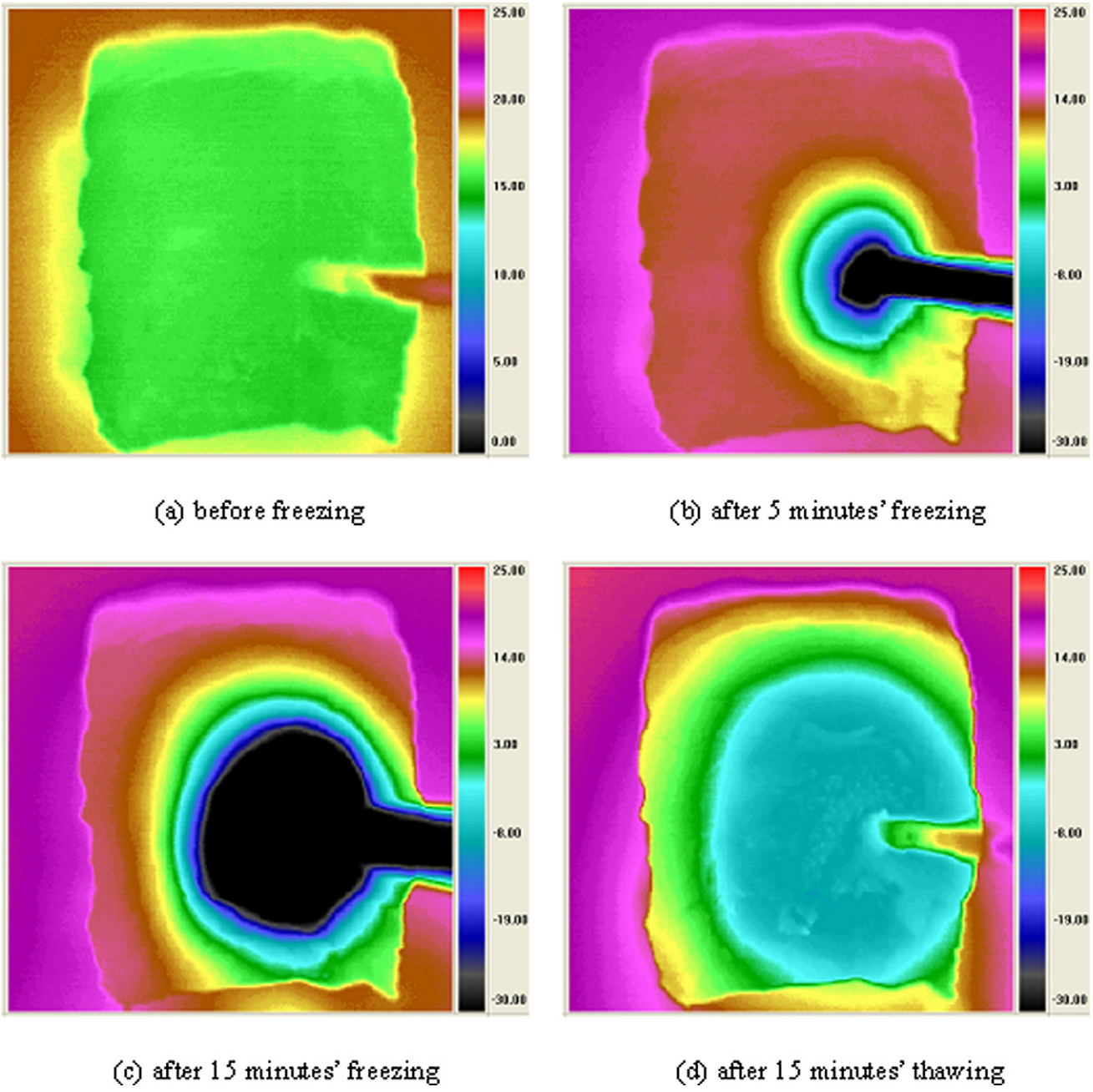

Fig. 9. Infrared thermographs for the case with no large blood vessel (in vitro tissue experiments).

control of blood flow such as vascular inflow occlusion may also be used to realize this purpose.

3.3. Animal experiments

Parts of representative infrared thermographs for animal experiments are shown in Fig. 13 and Fig. 14, respectively. The infrared thermographs for cryosurgical process of rabbit ear are given in Fig. 13, in which the distribution of superficial blood vessel in rabbit ear is clearly shown. During freezing, the temperature of rabbit ear surrounding the major vessel is obviously higher than that at other area. Similarly, the temperature in ear tissue adjacent to the major vessel varies more quickly than that in other region during thawing. After fully thawed, the thermograph of rabbit ear is extremely similar to that before freezing, as shown in Fig. 13(a) and Fig. 13(d) respectively. This phenomenon indicates that the vascular system of rabbit ear has not been irreversibly destroyed during the freezing process, and that when the large blood vessels with important function are embedded in or close to tumor (surgical removal of tumor has significant risk for this case), cryosurgical treatment for such tumor is still feasible.

The infrared thermographs for cryosurgical process of rabbit stomach are given in Fig. 14, in which the center of iceball produced at the freezing process clearly deviates from the position of cryoprobe. Comparing with Fig. 4(b), in which the network

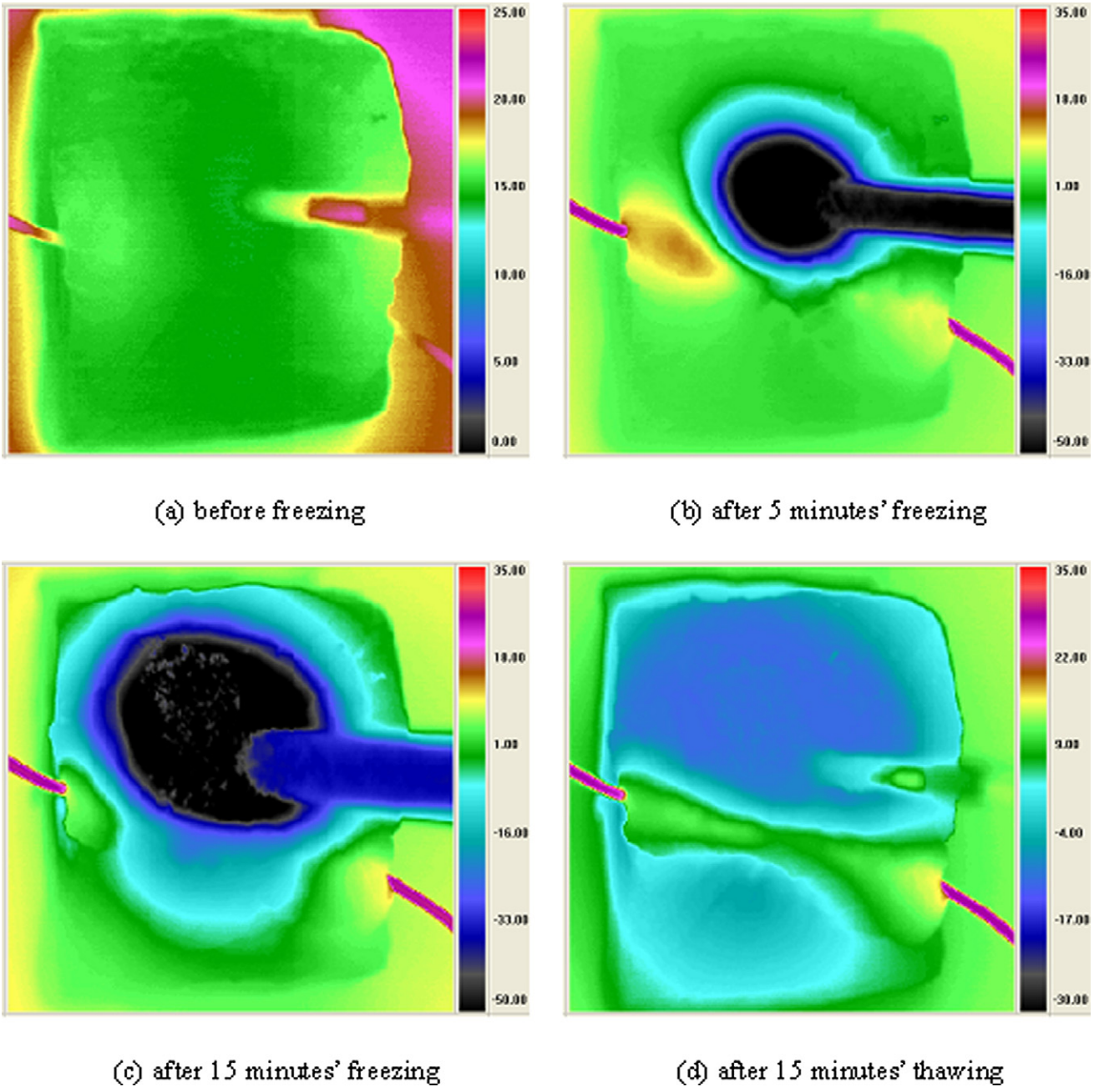

Fig. 10. Infrared thermographs for the case with a single large blood vessel (in vitro tissue experiments).

of large vessels at the region pointed out by the white arrow is extremely rich, it is not difficult to see that the principal direction for iceball formation is along the area without or being short of large vessels, and that the vessel-rich area (as pointed out by the white arrow) has obviously restrained the formation of iceball. Moreover, the heat source effects of large blood vessels can be clearly seen by comparing Fig. 4(a) and Fig. 14(b). It is indicated that the vessel-rich tissue is harder to be frozen during cryosurgery. This phenomenon should be fully considered in cryosurgery. Otherwise, the heating effects of large blood vessels during cryosurgery may result in inadequate freezing and then contributing to incomplete killing of tumor. In clinics, control of the inflow flux in the large blood vessels can certainly enhance the freezing damage to tumor, but the proper protection of large vessels should be taken at the same time.

4. Discussion

As is well known, tumor growth and survival ultimately depend on its blood vessel network, which results in the fact that tumors are often embedded with or close to some large blood vessels. In the presence of tumor involvement of vessels, surgical resection has many potential risks for the patient [22]. In these cases, the use of cryosurgery often appears as an attractive choice [11]. In order to perform a successful cryosurgical treatment on tumor when large vessels were presented, it is im-

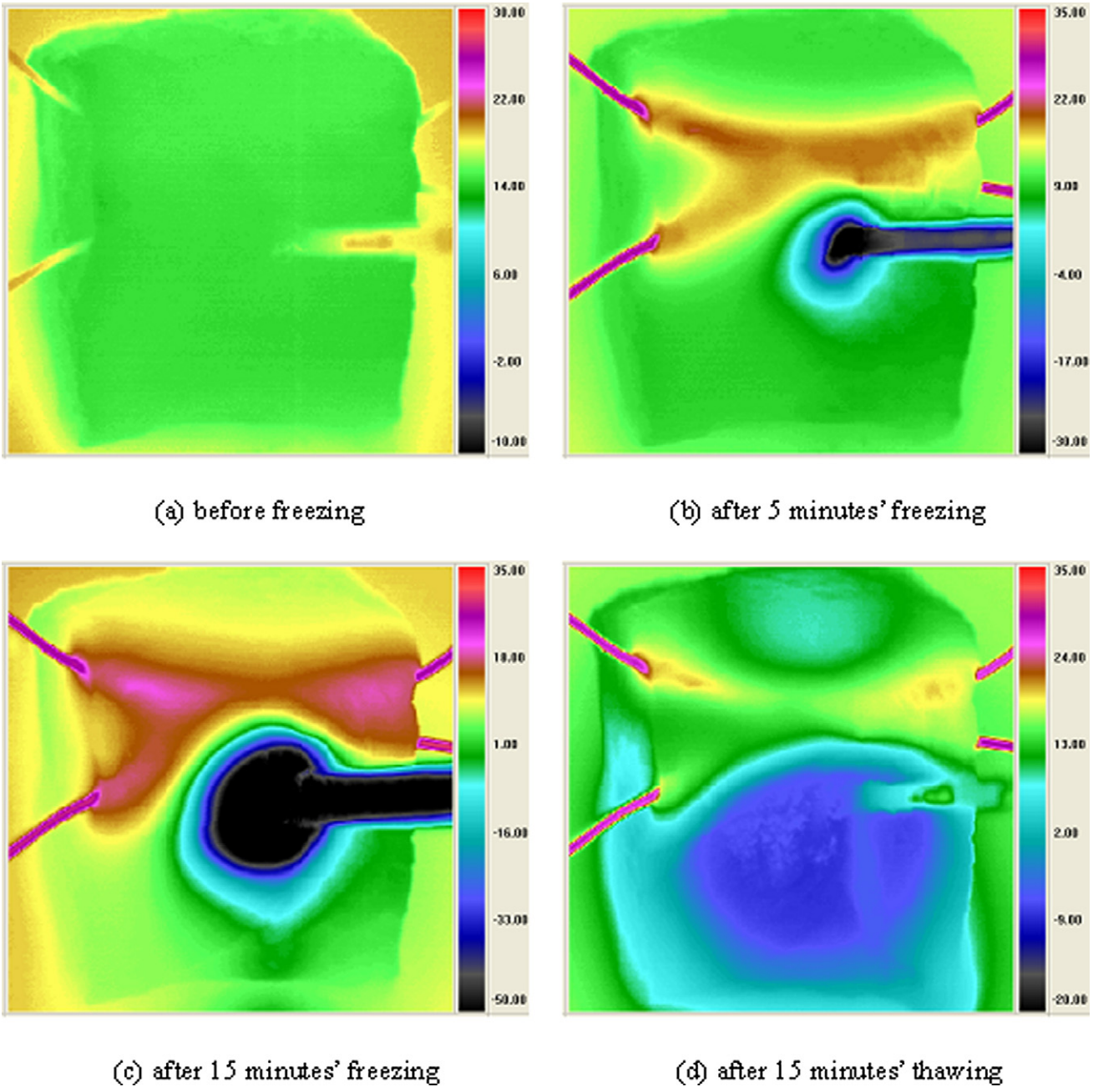

Fig. 11. Infrared thermographs for the case with parallel counter-current vessel pairs, in which the cryoprobe is vertical to the simulated vessel (in vitro tissue experiments).

portant to better understand the thermal effect of large vessel to the target tissues during freezing. The present experiments demonstrated, using infrared thermographic system for the first time, the influence of the single large vessel, the counter-current vessel pairs and the real tissue vasculature with large vessels to the temperature responses of tissue phantom, in vitro tissue and in vivo tissue subjected to freezing, respectively.

It has been shown that the different distributions of large vessels result in significantly different temperature responses for a given freezing pattern. In particular, the extents of both iceball and tissue necrosis, which can be evaluated from the tissue temperature distribution, vary significantly. The impact of these different large vessel patterns on the cryosurgical temperature responses are clearly shown from Fig. 6 to Fig. 14. It discloses that without paying enough attention on such thermal effect of large blood vessel, cryosurgical treatment on tumors embedded with or close to large vessels may turn out to be failed. Although experimental investigation on the thermal effect of large vessels with complex configurations such as counter-current vessel pairs and in vivo vascular network has been conducted in this study, additional experiments are still necessary on more complex cases such as considering the influences of vessel types (with different diameters and blood flow velocities) and multiple cryoprobes.

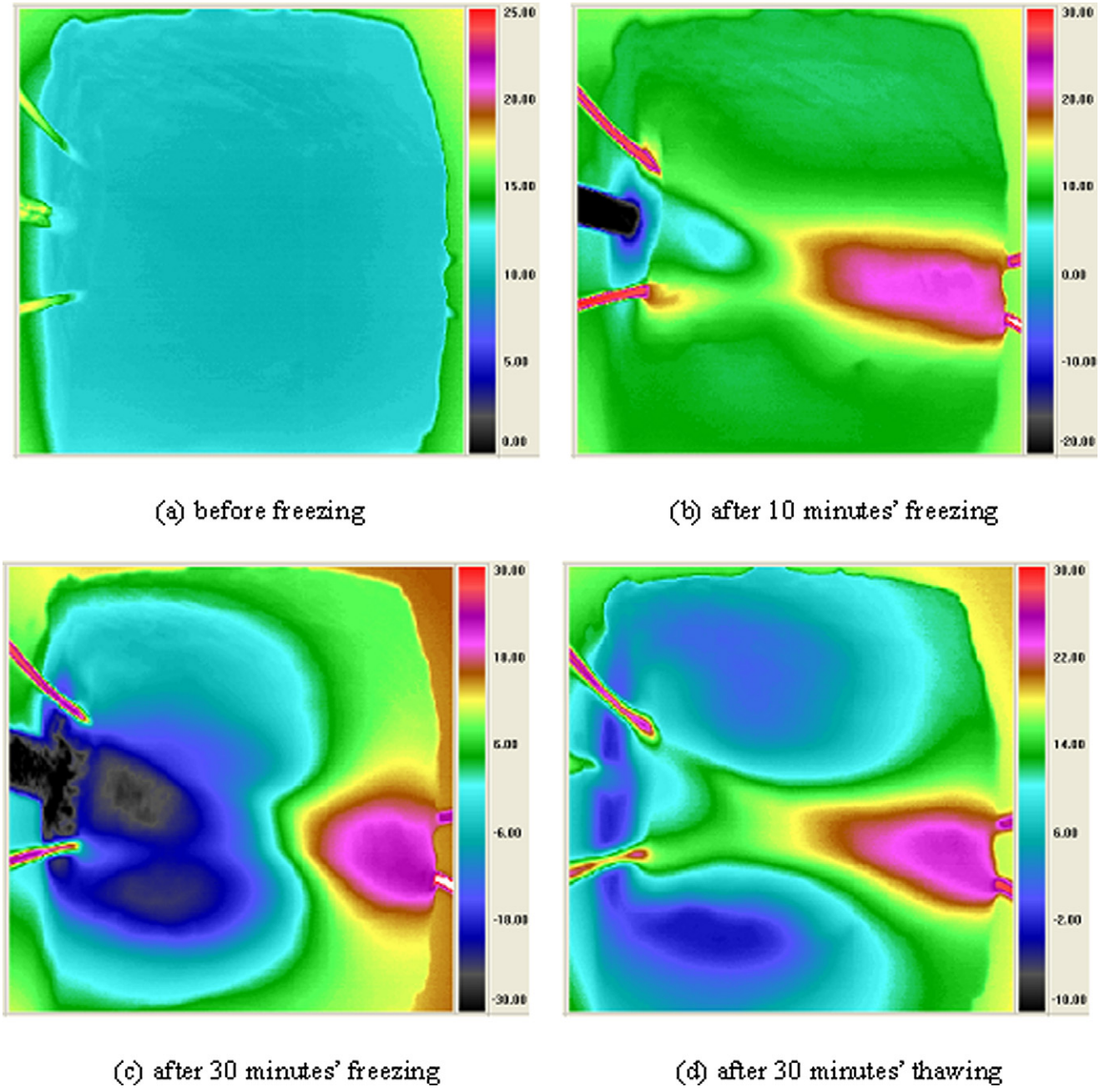

Fig. 12. Infrared thermographs for the case with parallel counter-current vessel pairs, in which the cryoprobe is parallel to the simulated vessel (in vitro tissue experiments).

Recent investigations have shown that local recurrence of tumor in an area treated with cryosurgery can occur at rates from 5% to 44% of patients [23,24]. This indicates that partial area of the tumor was not completely killed with freezing. This occurs most frequently if the original tumor was embedded with or near large blood vessels. In the experimental results of this study, there is evidence to indicate that, due to the so-called heat source effect, in the vicinity of large vessels, insufficient freezing or necrosis can be achieved because the blood flow provides a continuous source of heat. Therefore, if the thermal effects of large vessels were not considered in cryosurgical treatment planning, recurrence of tumors in the cryolesion may occur in the vicinity of large vessels after treatment. In this case, the persistence of vital tumor cells close to vessel walls or in the vessel walls is possibly responsible for the tumor recurrence. For shielding the tumor to be frozen from the continuous heating of blood flow in large vessels, the most direct method is to place the cryoprobes as close as possible to the large vessels. Besides, the availability of the technique of vascular occlusion or exclusion also provides another possible approach for such purpose. Recent studies indicated that selective vascular inflow occlusion additionally increases the volume of the lesion and may therefore be most attractive for successful clinical application [10,24]. However, the need of a major surgical procedure for

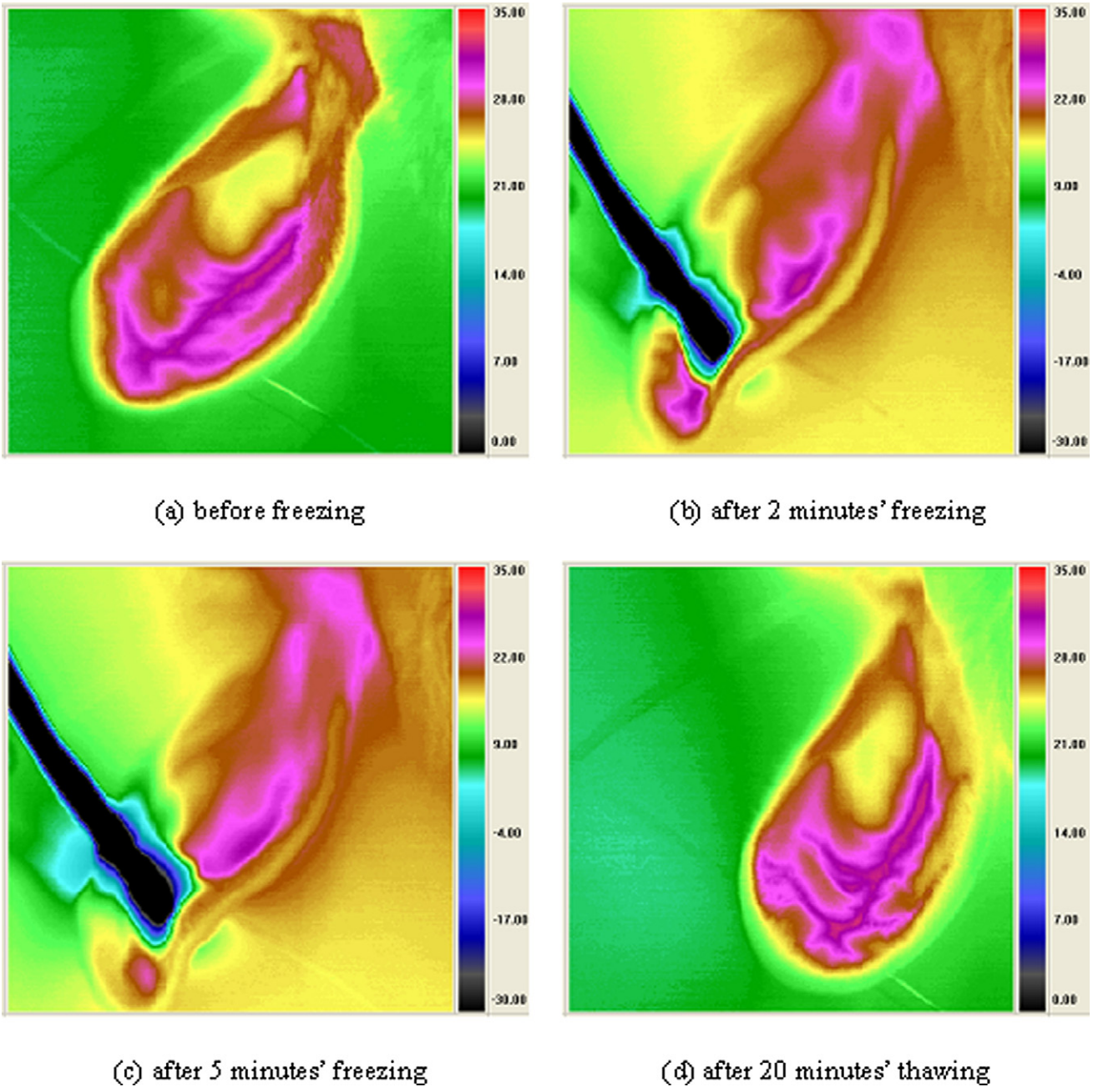

Fig. 13. Infrared thermographs for rabbit ear (animal experiments).

vascular exclusion negates minimally invasive surgery, which is one of the major advantages of percutaneous or laporoscopic cryosurgery. For some major vessels with important function, placing cryoprobes too close to them or vascular occlusion may lead to necrosis of these vessels, consequently resulting in some severe postoperative complications. Such issue should be realized when performing cryosurgery in the presence of large vessels.

To perform a cryosurgical procedure successfully, it is important to monitor the freezing extent and necrosis region during cryosurgery. Failure to do so accurately can result in either insufficient or excessive of freezing. Consequently, recurrence of tumors or destruction of healthy tissues may occur after or during cryosurgical treatment. Currently, several imaging techniques such as ultrasound [25], CT [26] and MRI [27] have been adopted in clinics to play the role of monitoring a cryosurgical procedure. Among them, ultrasound and CT cannot monitor the tissue temperature, and only be used to detect the boundary of iceballs produced by freezing. Although the temperature distribution of tissues during cryosurgery can be evaluated by MRI, and the necrosis region can thus be estimated by the lethal freezing temperature of tumor cells, the precision of temperature measurement by MRI is relatively coarse as compared with other temperature measurement methods. The experimental results presented in this study also indicate that using infrared thermography to monitor cryosurgical procedure of superficial

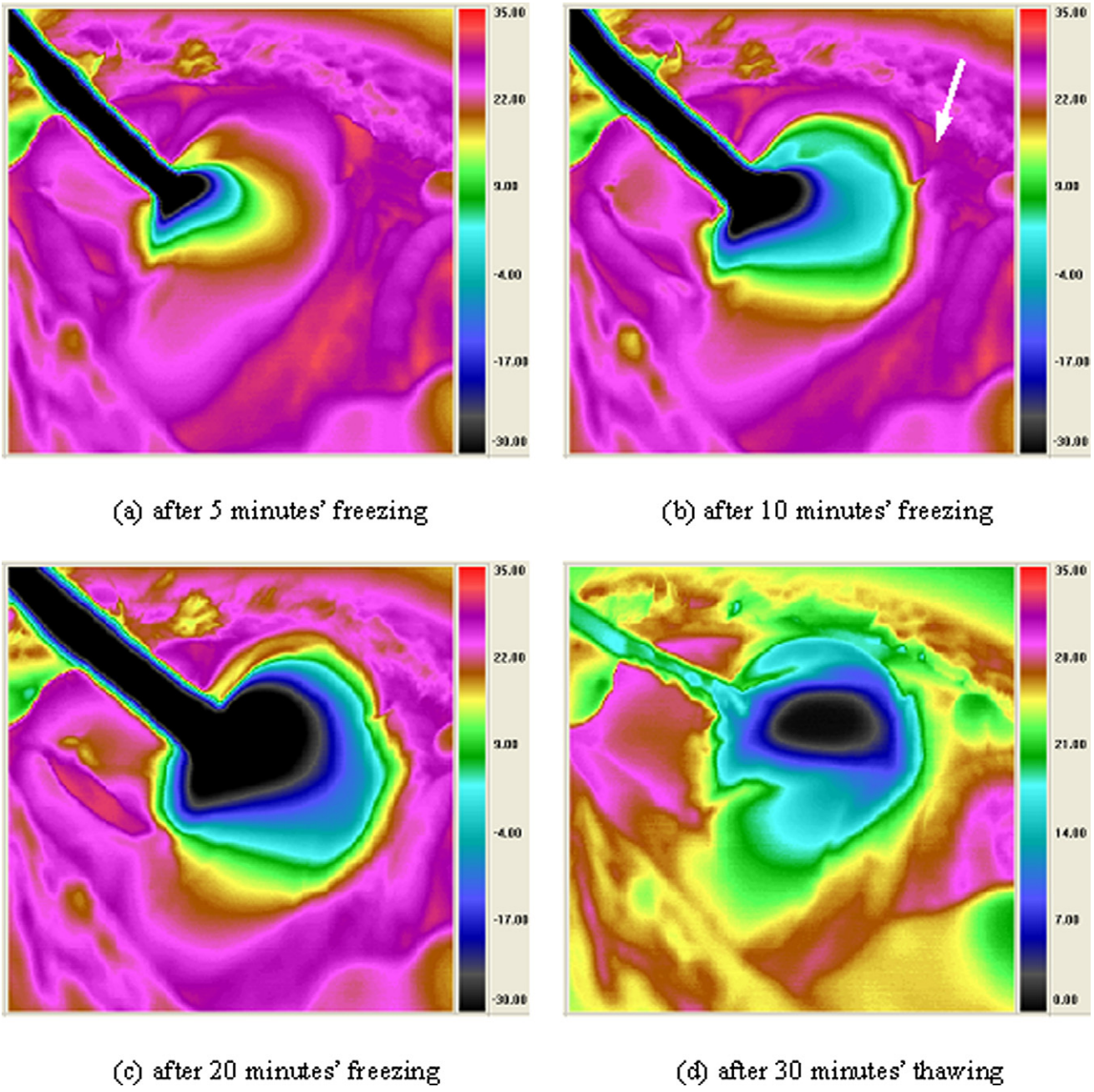

Fig. 14. Infrared thermographs for rabbit stomach (animal experiments).

tumor is technically feasible. As shown from Fig. 5 to Fig. 14, the transient temperature distributions can be directly read from the corresponding thermographs. With the information of temperature distributions, the freezing extent and necrosis region can be possibly obtained. Along this direction, performing histological investigation would be a good proof to show in which area of infrared zone cell death occurs from cryoablation, particularly in the area of uncertain margins. In fact, such feature has been noticed by several researchers [28,29]. However, clinical use of infrared imaging approach to monitor cryosurgical procedure is still unavailable up to now. Because infrared thermography has the advantage of being totally noninvasive and risk free, cost-effective, and quick and easy to perform, it would be very hopeful to serve as a valuable approach for monitoring cryosurgical procedure of superficial tumors. Further efforts are strongly needed to probe into such important issues.

Since different tissues or organs significantly vary from each other in their vasculature, a complete understanding of the thermal effect of large blood vessel in cryosurgery must be very difficult. To better understand such effect of large vessels, a lot of either theoretical or experimental works are needed. In our previous work, several typical vascular models have been developed to study the effects of large blood vessels to the tissue temperature distributions during cryosurgery. Readers are referred to [8] for more details. Clearly, the experimental results presented in this study can qualitatively support the previ-

ous theoretical research. But a benchmark comparison between them still needs tremendous efforts in the near future.

5. Conclusions

In this study, both simulated and animal experiments were performed to probe into the thermal effects of single large blood vessel and two counter-current vessels on the tissue temperature responses during cryosurgery. The experiments demonstrated the significant heating effects of large vessels in the frozen tissues. In cryosurgery, if the thermal effect of large blood vessels embedded in or close to tumor was not considered, the heat source effect of large vessels during freezing may result in inadequate freezing power and then contributing to non-killing of part of tumor. These results have disclosed the importance of considering the vasculature for cryosurgery. It should be pointed out that although very complex cases such as counter-current vessel pairs (in simulated experiments) and real tissue vasculature (in animal experiments) were already included in the present study, additional efforts (both from theoretical and experimental approaches) are still needed to further understand the thermal effect of large vessel in the frozen tissues, in order to perform a successful cryosurgical treatment for tumor in presence of large vessels.

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