Multiple-electrode radiofrequency ablations using Octopus® electrodes in an *in vivo* porcine liver model

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Objectives: The objective of this study was to determine the *in vivo* efficacy of radiofrequency ablation (RFA) in porcine liver using Octopus® electrodes for creating a large coagulation compared with RFA using clustered electrodes.

Methods: A total of 39 coagulations were created using a 200-W generator and clustered electrodes or Octopus electrodes during laparotomy in 19 pigs.

Radiofrequency was applied to the livers using four protocols: (1) Group A-1, monopolar mode using a clustered electrode ($n=11$); (2) Group A-2, monopolar mode using an Octopus electrode ($n=11$); (3) Group B-1, consecutive monopolar mode using three, clustered electrodes ($n=8$); and (4) Group B-2, switching monopolar mode using two Octopus electrodes ($n=9$). The energy efficiency, shape, diameters (D) and volume (V) of the coagulation volume were compared in each of the two groups.

Results: The mean maximum D and V of the coagulations in Group A-2 (4.7 cm and 33.1 cm³, respectively) were significantly larger than those in Group A-1 (4.1 cm and 20.3 cm³, respectively) ($p<0.05$). Furthermore, the mean minimum D, maximum D and V of the coagulations in Group B-2 were significantly larger than those in Group B-1, *i.e.* 5.3 vs 4.0 cm, 6.6 vs 4.9 cm and 66.9 vs 30.2 cm³, respectively ($p<0.05$). The energy efficiencies were also significantly higher in Groups A-2 and B-2 than in Groups A-1 and B-1 ($p<0.05$).

Conclusion: The Octopus electrodes were more efficient for creating a large ablation zone than clustered electrodes, and the efficacy of RFA with Octopus electrodes can be amplified in the switching monopolar mode.

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In recent years, image-guided percutaneous tumour ablation using radiofrequency (RF) energy has become increasingly popular and has gained wide acceptance as a valuable, minimally invasive treatment for primary and secondary liver malignancies [1]. Compared with conventional surgery, RF ablation (RFA) has many advantages in terms of reduced complications, morbidity and mortality as well as its cost-effectiveness. However, a major obstacle preventing the widespread use of RFA is its inability to reliably create adequate volumes of complete tumour destruction with sufficient safety margins, thus causing an increasing rate of marginal recurrence in large tumours due to the incomplete RFA. Most clinically available electrodes, including internally cooled electrodes, clustered electrodes, multitined expandable needle electrodes and perfusion electrodes, can induce coagulation necrosis in the range of 3–4 cm in diameter after a single ablation session [2, 3]. Therefore, to treat liver tumours >3 cm in diameter, multiple overlapping ablations are often required to cover the entire tumour volume as well as the peripheral ablation margins [4, 5]. However, in clinical practice, there is considerable difficulty repositioning the probe under ultrasound guidance during overlapping

ablations as numerous microbubbles form in the heated tissue during RFA and may thus interfere with finding the electrode tip and the untreated portions of the target tumour on ultrasound [6].

In order to avoid problems related to multiple overlapping ablations, including technical difficulties and a long procedure time, several approaches have been used to treat medium and large liver tumours. These include the use of cluster electrodes [7], multitined electrodes with saline infusion (RITA Medical Systems, Mountain View, CA) [2] and multiple electrodes in the switching monopolar mode or multipolar mode [8–11]. Although several previous studies demonstrated that the use clustered electrodes or multiple electrodes in the switching or multipolar modes could create larger coagulations [2, 3, 6, 8–14], they also presented several potential unsolved problems. The clustered electrode problems include: (1) convergence of the three individual needles <5 mm; (2) limited access to the target tumour owing to narrow intercostal spaces; and (3) displacement of the liver due to its resistance to the electrode. Although RFA using multiple electrodes can successfully treat large liver tumours, it is still not widely used in clinical practice, primarily owing to its high cost and the complexity of using multiple electrodes.

Recently, in order to improve the efficiency of clustered electrodes in creating a large ablation zone and to diminish any potential problems, we developed a separable clustered electrode (Octopus®; Taewoong

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Medical Co., Ltd, Goyang, Republic of Korea) with a specialised handle that can be incorporated into a larger handle in a single unit (Figure 1). Our electrode can be placed as a single electrode with variable interelectrode distances, according to the shape and size of the target tumour, or in a similar way to the clustered electrodes that are also composed of three electrodes as a single body at a fixed 5-mm interelectrode distance. Therefore, prior to their clinical application, we attempted to prove the *in vivo* efficacy of RFA using the Octopus electrodes to create a large area of coagulation necrosis in either the conventional or switching monopolar mode compared with RFA using a clustered electrode in porcine liver.

Methods and materials

Institutional Animal Care and Use Committee approval (IACUC No. 09-0078) was obtained for this animal study from the Department of Radiology, Seoul National University College of Medicine.

Radiofrequency equipment

In this experiment we used a multichannel RF generator (SSP-2000; Taewoong Medical Co., Ltd) consisting of

three generators with a maximum power of 200 W at a frequency of 480 kHz. With the multichannel RF generator, either a conventional or a switching monopolar mode can be used depending on the operator's intention [8]. In addition, in order to create coagulation necrosis, in this study we used either an Octopus electrode with 2.5-cm-long active tips or a clustered electrode with 2.5-cm-long active tips (Cool-tipTM; Covidien, Burlington, MA).

Design of the Octopus electrode

The Octopus electrode was developed in order to improve the efficiency of RFA in creating a large ablation area and to solve the known problems in the use of the clustered electrode. The Octopus electrode is composed of three cooled-tip electrodes each with a 2.5-cm active tip similar to that of the clustered electrode. However, it differs in three ways from the clustered electrode: (1) each single needle of the Octopus electrode consists of a metal electrode part and a specialised handle part, both of which can be incorporated into a larger handle in a single unit; (2) a cable part composed of three 50-cm-long independent cables for each needle and another 1-m-long conjoined single cable; and (3) three adapters for each port in the multichannel generator (Figure 1). Therefore, our electrode can be placed in the liver, as a single electrode with variable interelectrode distance, according to the

Figure 1. (a,b) Photographs of the Octopus[®] electrodes (Taewoong Medical Co., Ltd, Goyang, Republic of Korea), all of which have three individual needles. (c) Adaptor for the Octopus electrodes which connects the three cables to one port. (d) An illustration, which shows details of the connection between the needles and radiofrequency (RF) ablation system in a three Octopus electrodes system.

tumour size, while the conventional clustered electrodes are composed of three electrodes as a single body at a fixed 5-mm interelectrode distance. In addition, using a special connector which can merge three adaptors into a single adaptor, each needle electrode of the Octopus electrode can be used simultaneously in monopolar mode, similar to the clustered electrode (Figure 1c). Therefore, depending on the operator's intention, during RFA using the Octopus electrode, RF energy can be applied to the target tissue either in the simultaneous monopolar mode or in the switching monopolar mode. Given that the multichannel RF generator is composed of three generators with an independent port and an Octopus electrode is composed of three needle electrodes, if Octopus electrodes are used with the special connector, a maximum of nine needle electrodes (Figure 1d), *i.e.* three Octopus electrodes with three needle electrodes, could be used to deliver RF energy in the switching monopolar mode.

In vivo experiments: animals, anaesthesia and surgery

We obtained approval for this protocol from the Animal Care and Use Committee of our institution. All experiments were designed and performed in accordance with the general guidelines issued by the National Institutes of Health for the care of laboratory animals [15]. For the surgery we placed 19 domestic male pigs (mean weight, 70 kg) under inhalational anaesthesia using isoflurane (IsoFlo; Abbott Laboratories, Abbott Park, IL) after an intramuscular injection of 30 mg kg⁻¹ of zolazepam hydrochloride (Zoletil; Virbac, Carros, France) and 5 mg kg⁻¹ of xylazine (Rumpun; Bayer Korea, Ansan, Republic of Korea). The pigs were placed in a supine position and were draped in aseptic technique. After draping, an upper midline incision was made which extended from the xiphoid process to the umbilicus. In order to minimise potential variations in the RFA procedures, two authors (LES, CSH) performed all of the ablations, with up to three ablations performed in each pig during the entire experiment.

The current *in vivo* experiment was performed using two groups, A and B (Figure 2). To compare the efficiency of clustered electrodes and Octopus electrodes, a total of 22 RF-induced coagulation lesions were created in Group A: Group A-1, monopolar RFA using a single clustered electrode with a 0.5-cm interelectrode distance ($n=11$); Group A-2, monopolar RFA using a single Octopus electrode with a 1-cm interelectrode distance between three individual electrodes ($n=11$). RF energy was delivered to the electrodes for 18 min, and energy delivery was done at maximum wattage, *i.e.* 200 W, using an impedance-controlled algorithm to optimise energy administration to the tissue.

In Group B, the performance of three clustered electrodes was compared with that of two Octopus electrodes: Group B-1, monopolar RFA using three clustered electrodes with an interelectrode distance of 4 cm ($n=8$); and Group B-2, switching monopolar RFA using two Octopus electrodes consisting of six individual electrodes arranged in a pentagonal fashion with an additional electrode in the centre, 2 cm from the others ($n=9$). Based on the previous *ex vivo* optimisation study,

RF energy was delivered to the electrodes for 36 min in Group B-1 and for 24 min in Group B-2.

Assessment of coagulation necrosis

The pigs were sacrificed by intravenous potassium chloride injection administered 8 h after the procedure, and their livers were removed *en bloc*. The livers containing RF-induced coagulation were sliced in the transverse plane perpendicular to the electrode tracks; these slices were then cut again parallel to the electrode tracks. A histopathological study was then conducted on the specimens obtained and included mitochondrial enzyme activity staining by incubating the representative tissue sections for 30 min in 2% 2,3,5-triphenyl tetrazolium chloride or in 2,3,5-triphenol tetrazolium chloride (Sigma, St Louis, MO) at 20–25 °C. This test was used to determine the possible existence of irreversible cellular injury sustained during the early stages of RF-induced necrosis. Because the unstained region had been shown to correspond to the zone of necrosis, two observers measured the maximum diameter (D_{mx}), minimum diameter (D_{mi}) and vertical diameter (D_v) of the central, white region of the RFA zones on the slice, showing its maximum area as determined by consensus. In case of clover-leaf-shaped coagulation lesions, we drew an ellipse passing through three tangent points and measured the maximum diameter (D_{mx-eff}) and minimum diameter (D_{mi-eff}) of the ellipse (Figure 3). We regarded the ellipse as an effectively coagulated area that was sufficiently ablated by overlapping. To determine the volumes of the clover-leaf-shaped RF zones, we assumed that each coagulation zone was a sphere and used one of the following formulas: $\text{volume} = \pi \times 1/6 \times (D_{mx} \times D_{mi} \times D_v)$ or $\text{volume-eff} = \pi \times 1/6 \times (D_{mx-eff} \times D_{mi-eff} \times D_v)$.

In addition, the slices were then placed on an optical platform for photography (N90s; Nikon, Dusseldorf, Germany) and the images were saved to an image management software program (PhotoShop; Adobe, San Jose, CA). Area analysis was performed on a computer equipped with Image J software (<http://rsbweb.nih.gov/ij/>). The lesion shape was evaluated using a rough estimate of lesion "circularity" in two dimensions and then by computing the isoperimetric ratio for each lesion in the most representative slice. This value was computed using the following formula: $C(\text{circularity}) = 4\pi A \times l^{-2}$, where C is the isoperimetric ratio, A is the area of the measured zone and l is the perimeter obtained using the computer program NIH image J.

After gross examinations and analyses, all of the RF-induced ablated regions were fixed in 10% formalin for routine histological processing and were finally processed by paraffin sectioning and haematoxylin–eosin staining for a light microscope study.

Statistical analysis

For all *in vivo* experiments, the results were reported as mean $\pm$ standard deviation (SD). The minimum diameter of a coagulation zone perpendicular to the device axis (D_{mi} or D_{mi-eff}) and the coagulation volume or effective volume were used as measures for the primary

Figure 2. Diagrams of the radiofrequency ablation (RFA) protocol in each group. (a) Group A-1, monopolar RFA using single, clustered electrodes with a 0.5-cm interelectrode distance for 18 min ($n=11$). (b) Group A-2, monopolar RFA using single Octopus® electrodes (Taewoong Medical Co., Ltd, Goyang, Republic of Korea) with a 1-cm interelectrode distance between each of three individual electrodes for 18 min ($n=11$). (c) Group B-1, monopolar RFA using three, clustered electrodes with a 4-cm interelectrode distance for 36 min ($n=8$). (d) Group B-2, switching monopolar RFA using two, Octopus electrodes for a total of six individual electrodes with a 2-cm interelectrode distance and arranged in a radial fashion at angles of 60° for 24 min ($n=9$).

outcome in all statistical analyses. Student's *t*-test was used to identify significant differences in comparison of ablated area and energy efficiency in each group. We reported the *p*-values from these tests and defined statistical significance as indicated for $p < 0.05$. All statistical analyses were performed using SPSS® v. 15.0 software (SPSS Inc., Chicago, IL).

Results

Among the 19 pigs, all except for one successfully tolerated RFA under laparotomy. In all cases, the temperature of ablated area was maintained above 50°C during RFA. In one pig, sudden cardiopulmonary failure occurred right after the RFA procedure and

closure of the incision. An autopsy revealed that there was no severe bleeding, liver laceration or unexpected burn injury to the adjacent organs, although a thrombus was found in the hepatic vein.

Gross and histopathological results

Grossly, the ablated lesions were round or elliptical in shape in Groups A and B-2, but were clover-leaf-shaped in Group B-1 (Figure 4). Histopathologically, in all cases, the ablated regions demonstrated a central necrotic zone surrounded by a peripheral haemorrhagic zone consisting of necrotic hepatocytes, interstitial haemorrhage and polymorphonuclear leukocyte infiltrates. Within the central necrotic zone, no viable cells were found,

Figure 3. (a) Measurement of the coagulated lesion in clover-leaf-shaped necrosis by drawing an ellipse which passes by the three tangent points. We measured both the maximum and minimum diameters of the ellipse. (b) In cases of round- or oval- shaped coagulated lesions, we measured non-post-processing maximum and minimum diameter of those lesions.

Figure 4. Comparison of radiofrequency-induced coagulation in the four groups. (a) Group A-1, monopolar RFA using single, clustered electrodes with a 0.5-cm interelectrode distance for 18 min. (b) Group A-2, monopolar RFA using single Octopus® electrodes (Taewoong Medical Co., Ltd, Goyang, Republic of Korea) with a 1-cm interelectrode distance between each of three individual electrodes for 18 min. (c) Group B-1, monopolar RFA using three clustered electrodes with a 4-cm interelectrode distance for 36 min. (d) Group B-2, switching monopolar RFA using two Octopus electrodes for a total of six individual electrodes with a 2-cm interelectrode distance and arranged in a radial fashion at angles of 60° for 24 min.

although within some of the haemorrhagic lesions, areas of sinusoidal congestion and haemorrhage were accompanied by advanced necrotic changes and patches of living cells.

Dimension of the coagulation

The mean ablated volumes of Group A were 20.3 cm³ in A-1 and 33.1 cm³ in A-2. The mean diameters of D_{mx} , D_{mi} , and D_v were 4.1, 3.0 and 3.2 cm in A-1, respectively, and 4.7, 3.5 and 3.8 cm in A-2, respectively. The circularities of A-1 and A-2 were 0.75 and 0.78, respectively. Statistical significance was found in analyses of the volume ($p=0.007$) and D_{mx} ($p=0.046$) (Table 1).

In Group B-1, we evaluated the difference between wholly ablated lesions and effectively ablated lesions by overlapping. The mean values of D_{mx} and D_{mx-eff} (7.5 vs 4.9 cm, respectively), D_{mi} and D_{mi-eff} (5.4 vs 4.0 cm, respectively) and volume and volume-eff (61.1 vs 30.2 cm³, respectively) all differed significantly ($p<0.001$). The circularity of Group B-1 was 0.79.

When comparing the effectively ablated areas in Group B-2 with those in Group B-1, significant differences were also noted in a few of the parameters. The mean values of D_{mx-eff} (6.6 vs 4.9 cm), D_{mi-eff} (5.3 vs 4.0 cm) and volume-eff (66.9 vs 30.2 cm³) in B-2 and B-1, respectively, all differed significantly (Table 2). The circularity of Group B-2 was 0.82.

Electrical measurements

The mean $\pm$ standard deviation of the total delivered energy in groups A-1, A-2, B-1 and B-2 were 17.51 $\pm$ 4.91, 22.08 $\pm$ 3.40, 30.59 $\pm$ 6.14 and 29.89 $\pm$ 2.37 kcal, respectively. The delivered energy per effectively ablated volume, which means energy efficiency, was 1.22 $\pm$ 0.37 kcal cm⁻³ in Group A-1 and 0.81 $\pm$ 0.44 kcal cm⁻³ in Group A-2. This difference was statistically significant ($p=0.029$). The energy efficiency was 1.01 $\pm$ 0.33 kcal cm⁻³ in Group B-1 and 0.50 $\pm$ 0.17 kcal cm⁻³ in Group B-2. This difference was also statistically significant ($p=0.001$).

Table 1. The measured values of the dimensions of the ablation zones in Group A

Coagulation necrosis	Group A-1	Group A-2	p-value
D_{mi} (cm)	2.99 $\pm$ 0.45	3.49 $\pm$ 0.80	0.088
D_{mx} (cm)	4.09 $\pm$ 0.49	4.67 $\pm$ 0.75	0.046
D_v (cm)	3.20 $\pm$ 0.56	3.77 $\pm$ 1.01	0.122
Volume (cm ³)	20.27 $\pm$ 4.35	33.08 $\pm$ 13.41	0.007
Circularity	0.75 $\pm$ 0.11	0.78 $\pm$ 0.13	0.502
D_{mi} to D_{mx} ratio	0.73 $\pm$ 0.11	0.75 $\pm$ 0.11	0.761
Total delivered energy (kcal)	17.51 $\pm$ 4.91	22.08 $\pm$ 3.40	
Energy delivery time (min)	18	18	–
Energy per volume (kcal cm ⁻³)	1.22 $\pm$ 0.37	0.81 $\pm$ 0.44	

D_{mi} , minimum diameter of the central, white region of the radiofrequency ablation zones; D_{mx} , maximum diameter of the central, white region of the radiofrequency ablation zones; D_v , vertical diameter of the central, white region of the radiofrequency ablation zones.

Values are mean $\pm$ standard deviation.

Table 2. The measured values of the dimensions of the ablation zones in Group B

Coagulation necrosis	Group B-1	Group B-2	p-value
Dmi-eff (cm)	4.03 ± 0.40	5.30 ± 0.85	0.002
Dmx-eff (cm)	4.91 ± 0.26	6.60 ± 0.65	<0.001
Dv (cm)	2.86 ± 0.69	3.56 ± 0.75	0.067
Volume-eff (cm ³)	30.15 ± 9.91	66.88 ± 26.19	0.002
Circularity-eff	0.82 ± 0.08	0.82 ± 0.06	0.890
Dmi-eff to Dmx-eff ratio	0.82 ± 0.09	0.80 ± 0.06	0.575
Total delivered energy (kcal)	30.59 ± 6.14	29.89 ± 2.37	
Energy delivery time (min)	36	24	–
Energy per volume (kcal cm ⁻³)	1.01 ± 0.33	0.50 ± 0.17	

Circularity-eff, circularity of effectively ablated area; Dmi-eff, minimum diameter of an ellipse passing through three tangent points in an effectively coagulated area; Dmx-eff, maximum diameter of an ellipse passing through three tangent points in an effectively coagulated area; Dv, vertical diameter of the central, white region of the radiofrequency ablation zones; volume-eff, volume of effectively ablated area.

Values are mean ± standard deviation.

Discussion

In our study, we found that monopolar RFA using an Octopus electrode (Group A-2) with an interelectrode spacing of 1 cm was more effective for creating large coagulation areas, compared with conventional monopolar RFA using a clustered electrodes with a fixed spacing of 0.5 cm (Group A-1). We believe that this factor may contribute to lowering the local recurrence rate after RFA by ensuring a sufficient safety margin even with a single application of RF energy and it may also broaden the RFA indications to include large liver malignancies (>3.5 cm). Interestingly, in Group A-2 there were no RFA lesions that appeared separated or clover leaf shaped at an interelectrode spacing of 1 cm. Our results differed somewhat from those of a previous study by Goldberg et al [7], which demonstrated that a 5-mm interelectrode spacing was preferable to a 10- or 15-mm spacing for creating a single, united ablation zone because of the relatively poor heat conduction of the liver tissue [12–14, 16]. We believe that this discrepancy can be explained by the difference in maximum generator power and maximum currents (150 W in the previous study *vs* 200 W in our study), difference in the length of the active tips (2 *vs* 2.5 cm), the ablation time differences (10 *vs* 18 min) and the use of different experimental animals (*ex vivo* bovine explanted liver *vs in vivo* porcine liver). Based on our observations, we speculate that RFA using a multi-channel generator and an Octopus electrode at a 10 mm interelectrode spacing is able to create a united, large ablation by balancing heat conduction between the electrodes and the electrical interference (Faraday cage effect) [12–14, 16].

More importantly, in Groups B-1 and B-2, we compared the *in vivo* efficiency of switching monopolar RFA using two Octopus electrodes (a total of six individual needles and 24 min ablation time) to create coagulation with that of consecutive RFA with three clustered electrodes (a total of nine individual needles and 36 min ablation time). We found that switching monopolar RFA using two Octopus electrodes placed in a radial fashion at angles of 60° could create a significantly larger ablation zone and more effective volume than RFA using three clustered electrodes in a triangular fashion. We believe that the superior performance of switching monopolar RFA using two Octopus

electrodes may be attributable to the greater efficiency of the switching RFA mode for delivering RF energy to the target tissue than of overlapping ablations: 1.01 ± 0.33 *vs* 0.50 ± 0.17 kcal cm⁻³ [8, 17]. Furthermore, switching RFA using two Octopus electrodes created a larger effective volume than overlapping RFA using three clustered electrodes, and the shape of the ablation zone in Group B-2 was more circular than that in Group B-1 (0.79 *vs* 0.82). Therefore, we expect that switching monopolar RFA using Octopus electrodes can improve the therapeutic efficiency of RFA for treating large liver tumours by creating a larger effective volume of ablation zone in a circular shape and at a lower risk of complications owing to the decrease in the number of electrodes used.

In terms of complications, there was one RFA mortality case (1/19, 5.3%) in which two sessions of RFA were performed sequentially, according to the Group B-1 and B-2 protocols. Immediately after the RFA procedure, both the oxygen saturation in the blood and the blood pressure began to decline during the peritoneal suturing, thus leading to the fatal outcome. An autopsy found that the RFA was successful and that there was no evidence of bleeding, laceration of the pig's liver, burn injury to adjacent organs or severe complications related to the RFA procedure except for the small amount of intrahepatic venous thrombi. We speculated that a pulmonary embolism might have led to the respiratory failure; however, we found no conclusive evidence of this having occurred.

Based on our study results, we believe that the multiple electrodes approach in switching RFA mode using Octopus electrodes can improve the therapeutic efficiency of RFA for hepatic malignancy by effectively creating a larger ablation. Currently, RFA procedures are widely performed at many hospitals using a single electrode, a cooled-tip electrode, a clustered electrode or an umbrella-type electrode [18–21]. However, in a large number of cases, this approach requires overlapping ablations in order to create a sufficient number of safety zones around the target tumour [4–5]. In fact, the most demanding technical difficulty in performing overlapping ablations using a single electrode is related to the echogenic bubble clouds created during the RFA procedure [6] and which may result in a higher local recurrence rate than surgical resection [22, 23]. We believe that RFA using the Octopus electrode may alleviate this technical problem.

There were a few limitations to our study. Firstly, despite the selective use of adult pigs each weighing more than 70 kg, their livers were not large enough to allow comparison of the *in vivo* RFA efficiency of the Octopus electrode and the clustered electrode. In that respect, a pig may not be the ideal animal on which to test the efficiency of the Octopus electrode, although there is currently no better animal model. Secondly, as all RFA procedures were performed at laparotomy under ultrasound guidance, it was therefore convenient for us to control the interelectrode distance and determine the entry site of the electrode according to our study protocol. On the other hand, considering that many standard RFA procedures are carried out via the percutaneous approach under image guidance using ultrasound, CT or MRI, it might be technically difficult to maintain the ideal interelectrode distance from the entry site to the target tissue using the Octopus electrodes [24]. Nonetheless, characteristic anatomical features of the pig, such as the spatial overlapping of its five hepatic lobes and its relatively thick abdominal wall, caused serious technical difficulties with RFA via the percutaneous approach and thus led us to choose laparotomy. Thirdly, post-RFA follow-up was limited to only 8 h. The length of the observation time might have been long enough to evaluate the short-term safety of RFA using Octopus electrodes; however, the long-term safety still remains questionable. Lastly, placement of multiple Octopus electrodes at regular, interelectrode spacing under image guidance might be difficult in percutaneous RFA procedures. However, this might not be a serious problem on laparotomy, and, therefore, our study results may be more easily applicable to intra-operative RFA for treating patients with large liver tumours.

In conclusion, the Octopus electrode with an inter-electrode distance of 1 cm is superior to the clustered electrode for creating a large coagulation using a conventional monopolar mode. Furthermore, the efficacy of Octopus electrodes can be increased in a multi-electrode model by applying switching monopolar RFA.

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