Radiofrequency Liver Ablation: Experimental Comparative Study of Water-Cooled Versus Expandable Systems

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OBJECTIVE. We evaluate the uniformity and reproducibility of thermal lesion ablation and quantify the volume of tissue destruction and hemorrhage induced with two different commercially available radiofrequency ablation devices.

MATERIALS AND METHODS. A four-array anchor expandable needle electrode and a triple-cluster cooled-tip needle electrode were used to induce lesions in three explanted calf livers and in vivo in eight swine livers. The sizes of the radiofrequency-induced lesions were macroscopically evaluated by measuring two perpendicular dimensions immediately after the experiment. Bleeding was evaluated by weighing gauze swabs used to dry the hemorrhage caused by electrode insertions.

RESULTS. In explanted liver, the mean diameter of the radiofrequency-induced lesion was 5.3 ± 0.7 cm for the cooled-tip needle and 3.7 ± 0.4 cm for the expandable needle (p = 0.042), which correspond to approximate volumes of 65.35 ± 26.22 cm^3 and 26.67 ± 9.59 cm^3, respectively ($p < 0.002$). In vivo, the mean diameter was 3.7 ± 0.4 cm for the cooled-tip needle and 3 ± 0.4 cm for the expandable needle ($p < 0.0001$), which correspond to approximate volumes of 24.18 ± 7.56 cm^3 and 11.16 ± 3.65 cm^3, respectively ($p < 0.0001$). Blood loss attained a median value of 3.5 g for the cooled-tip needle and 2.6 g for the expandable needle; this difference was not statistically significant ($p = 0.06$).

CONCLUSION. The cooled-tip needle induced significantly larger lesions than the expandable needle, but the lesions produced by the expandable needle are more reproducible, uniform, and spheric. The larger size of the lesions produced by the cooled-tip needle may be attributed to the higher maximum power used by the generator and the higher energy deposition, which is due to the cooling of the needle electrode.

Radiofrequency ablation is a recently introduced technique, either percutaneous or intraoperative, for the treatment of primary and secondary liver tumors; application of this procedure is rapidly gaining momentum [1–7]. Radiofrequency current generates the displacement of molecules back and forth, and this ionic agitation is converted into frictional heat [8, 9]. Heating tissues to more than 50°C leads to the breakdown of proteins and membrane, which results in cellular death.

When an exposed single radiofrequency electrode is used in liver parenchyma in vivo, radiofrequency-induced lesions measure approximately 1.5 cm in diameter [10–12], which is not sufficiently large to eradicate most hepatic tumors. A renewal of interest in this technique for treatment of liver tumors is mainly attributable to technical progress that allows the induction of larger lesions with a single needle electrode insertion. Excluding the use of bipolar radiofrequency [13] and the "wet needle" [14], which are not widely used in clinical practice today, two main strategies have been developed to enlarge radiofrequency-induced lesions: expandable multiple-array needle electrodes and electrode cooling.

The expandable multiple-array needle is an insulated needle containing hook-shaped inner electrodes that can be deployed like umbrella ribs once the outer needle has been inserted into the tissue targeted for destruction. In this manner, after a single needle insertion, radiofrequency can be applied at multiple sites, which has an additive effect, thus increasing the area of radiofrequency destruction [15]. The cooled-tip needle is made of a cluster of three single electrodes welded into three separate dual-lumen insu-

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lated cannulas with exposed tips of 2.5 cm in length. The cannulas are perfused with chilled saline to reduce the heat accumulated at the tip of each electrode, thereby allowing a higher current intensity to be deposited in tissue, especially tissue that is remote from the electrode [16]. Both methods rely on the fact that the sum of the simultaneous adjacent multiprong ablation is greater than if each prong had been inserted separately [4].

The aim of this study was to compare the size of radiofrequency lesions induced by two commercially available radiofrequency ablation systems, expandable needle and cooled-tip needle. We also evaluated blood loss caused by the needle electrode insertion with both devices.

Materials and Methods

Radiofrequency Systems

The cooled-needle radiofrequency system is a 480-kHz generator (CC1; Radionics, Burlington, MA) capable of producing a maximum power of 200 W through a 17-gauge monopolar cooled triple-cluster needle electrode. This triple-cluster needle electrode is composed of three single (parallel) cooled-tip needles spaced 0.5 cm apart and grouped equidistant in a triangular pattern, with a 2.5-cm active distal part in a single device (Fig. 1). Circuitry incorporated in the generator allows continuous monitoring of impedance between the active parts of the cooled-tip needle electrodes and the grounding pads placed on the thigh of the animal. A thermocouple embedded in the electrode ensures constant monitoring of the temperature at the tip of the needle.

In our experiment, a peristaltic pump (313FS/D variable-speed pump; Watson-Marlow, Paris, France) cooled the electrode internally by delivering chilled saline (0°C) in its cannula sheath at a flow rate that was sufficient to maintain the electrode temperature below 25°C. Radiofrequency current was emitted over 15 min per needle electrode insertion, with the generator set to deliver the maximum power in the autocontrol mode. The autocontrol mode allows the maximum power to be delivered until impedance rose to 10 Ω above the baseline value. At this point, the current switches off automatically to avoid a further increase in the tissue temperature that would result in charring. Tissue charring at the needle tip has an insulating effect, which decreases the energy deposition and the size of the thermal lesion. Fifteen seconds later, the current automatically switches on again, thus generating pulsed radiofrequency that has been shown to increase the size of the radiofrequency lesion [17].

The expandable needle radiofrequency system is a 460-kHz generator (model 500; RITA Medical Systems, Mountain View, CA) capable of delivering a maximum power of 50 W through a 15-gauge needle. The needle contains four hook-shaped electrodes that can be deployed 1.5 cm from the central needle cannula (Fig. 1); when the needles are fully deployed, the device is 3 cm in diameter. The needle is insulated with a 0.1-mm-thick plastic film and has a noninsulated 1-cm distal part that delivers radiofrequency current in addition to the four expandable electrodes. Each electrode has a thermistor at its tip to monitor temperature in the surrounding tissue. In our experiment, once the needle had been inserted and deployed in the liver parenchyma, the generator was used for 15 min in the mean-temperature-control mode with a threshold set at 95°C. This mode allows the delivery of the maximum power output until the mean value of the temperatures measured at the tip of the four electrodes reaches the threshold, whereupon the generator maintains this mean temperature by automatically adjusting power output.

Study Design

A series of radiofrequency thermal lesions were induced in explanted calf liver and in vivo in pig liver.

Four radiofrequency lesions were induced with each radiofrequency system in each of three explanted calf livers at room temperature so that 12 lesions were created ex vivo with each system. The needles were inserted at least 4 cm inside the liver parenchyma, and one ground pad was placed more than 20 cm from the distal tip of the electrode.

In accordance with legislation governing animal care, eight young Large-White swine weighing 60–85 kg were placed in the supine position and premedicated. The animals were intubated, and general anesthesia was maintained with methoxyfluorane throughout the experiments. Cardiac and respiratory

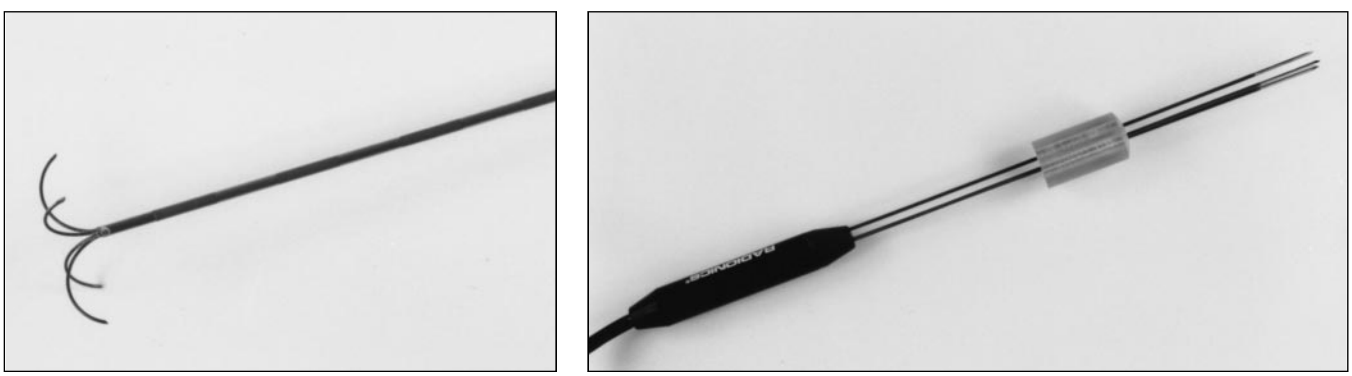

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Fig. 1.—Radiofrequency systems tested.
A, Photograph of tip of 15-gauge expandable needle shows four hook-shaped, expandable electrodes deployed.
B, Photograph of cooled-tip triple-cluster needle with 2.5-cm exposed active parts shows probe-guiding device and stabilizer threaded onto needle.
C, Photograph of two generators used for experiments. Generator for expandable needle is on left, and generator for cooled needle is on right.

parameters were monitored throughout the procedure. Four ground pads were placed for cooled-tip needle radiofrequency ablation, and one ground pad was placed for expandable needle radiofrequency ablation, as recommended by manufacturers of the systems.

A median laparotomy was preferred to the percutaneous approach under sonographic guidance for placement of the radiofrequency needle electrode, because laparotomy allowed more accurate quantification of blood loss after retrieval of the needle. Furthermore, the deep fissures that separate the swine liver lobes are difficult to visualize with sonography. Therefore, the risk of placing the active part of the radiofrequency needle straddling two lobes to create lesions that cannot be accurately evaluated is higher. Thus, after median laparotomy, needle electrodes were inserted without imaging guidance inside the liver, distant from the liver capsule. Two or three lesions were induced with each radiofrequency system in the liver of each animal. The position and order in which each lesion was induced were randomly assigned. A total of 18 sessions were performed in vivo with each radiofrequency system. Modification of blood flow to the liver was not attempted. Neither needle-track nor capsule cauterization was performed. After retrieval of each needle electrode, one or several preweighed gauze swabs were gently applied to the puncture site without pressure. Gauze swabs were maintained at the site until the swabs ceased to absorb blood from the puncture site. The gauze swabs were then weighed, and blood loss was evaluated by subtracting the initial dry weight from the final weight of the blood-saturated gauze swabs.

Immediately after the experiment, the animals were sacrificed, and the liver was explanted. Specimens were immediately cut into 5-mm-thick slices along the needle axis and macroscopically evaluated by measuring the two longest dimensions with calipers, one along the needle axis and the other perpendicular to it. Macroscopic changes in specimens have been shown to correlate well with coagulation necrosis at histopathologic examination [18]. Dimensions of the radiofrequency lesions were based on the consensus of three observers. The approximate volume of radiofrequency-induced lesions was evaluated by approximating them to a sphere using the following formula: $\Pi (d1 \times d1 \times d2) / 6$, where $d1$ is the diameter perpendicular to the axis of the electrode and $d2$ is the diameter along it. Although the two diameters perpendicular to the needle axis were not measurable for technical reasons, we used twice the only one diameter measured perpendicular to the needle axis because the third diameter should be close to it.

Statistical Analysis

The minimum and maximum lengths and approximate volumes for the radiofrequency lesions were recorded and are reported as means plus or minus the standard deviation. The measurements of lesions obtained with each system were compared using the *t* test. Variability in the size of lesions induced with the same system was compared with the F test for variance [19]. A median value is provided for blood loss because the distribution of values was not normal.

Results

The results of the experiments are summarized in Table 1, and results obtained for in vivo liver are shown in Figure 2.

Ex Vivo

Twelve lesions were induced with each system. For the lesions induced with the cooled-tip needle, the lengths ranged from 3.6 to 5.5 cm. For the lesions induced with the expandable needle, the lengths ranged from 3 to 4 cm. The mean lengths and approximate volumes for the lesions induced with each system are reported in Table 1. Differences between the expandable needle and the cooled-tip needle for the mean length ($p = 0.042$) and the estimated approximate volume ($p < 0.002$) were statistically significant. The coefficients of variability were statistically different ($p = 0.007$), with the expandable needle attaining 10% and the cooled-tip needle attaining 17%.

In Vivo

The eight pigs tolerated the procedures well, with no major variation in blood pressure.

The 18 lesions induced in the liver with the cooled-tip needle ranged in diameter from 3 to 4.3 cm. The lesions induced with the expandable needle that could be measured in 14 cases ranged in diameter from 2 to 3.2 cm. The mean lengths and approximate volumes for the lesions induced with each system are reported in Table 1. Differences between the expandable needle and the cooled-tip needle for the mean length ($p < 0.0001$) and the estimated approximate volume ($p < 0.0001$) were statistically significant. It is noteworthy that the longest dimension measured was parallel to the needle axis for the cooled-tip needle and was perpendicular to it for the expandable needle. The ratio of the longest axis to the shortest axis was 1.19 ± 0.14 for the cooled-tip needle and 1.12 ± 0.08 for the expandable needle ($p = 0.035$), which emphasizes the more spheric shape of the expandable needle when compared with the cooled-tip needle.

During four of the 18 sessions with the expandable needle, induced lesions were four separate spots of coagulation necrosis of less than 1

TABLE 1 **Dimensions and Approximate Volumes of Lesions Induced Ex Vivo and In Vivo by Radiofrequency Ablation with Cooled-Tip Triple-Cluster Needle System and Expandable Needle System**

Dimension Measured	Size of Lesion Induced by Radiofrequency Ablation (mean ± SD)			
	Ex Vivo Liver		In Vivo Liver	
	Cooled Needle	Expandable Needle	Cooled Needle	Expandable Needle
Length (cm)				
Shortest axis	4.61 ± 0.68	3.46 ± 0.5	3.41 ± 0.41	2.55 ± 0.44
Longest axis	5.90 ± 1	3.94 ± 0.38	4.03 ± 0.48	2.86 ± 0.4
Mean	5.26 ± 0.73	3.7 ± 0.41	3.72 ± 0.40	3 ± 0.37
Approximate volume (cm^3)	65.35 ± 26.22	26.67 ± 9.59	24.18 ± 7.56	11.16 ± 3.65

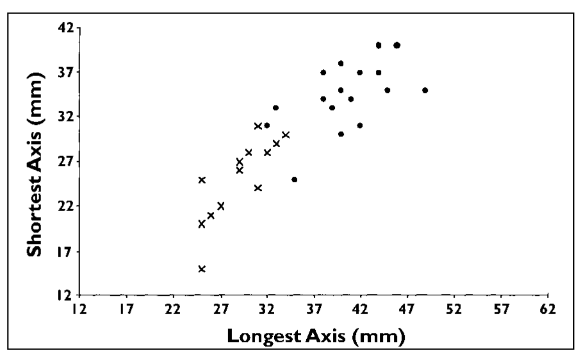


Fig. 2.—Diagram shows size of lesions induced by administration of radiofrequency with cooled-tip needle (●) and with expandable needle (×). Longest dimension is *x*-axis, and shortest dimension is *y*-axis. Note that lesions induced with cooled-tip needle electrode are larger than those produced with expandable needle electrodes. Also, note that expandable needle electrodes produced lesions that were more spheric than those produced with the cooled-tip needle.

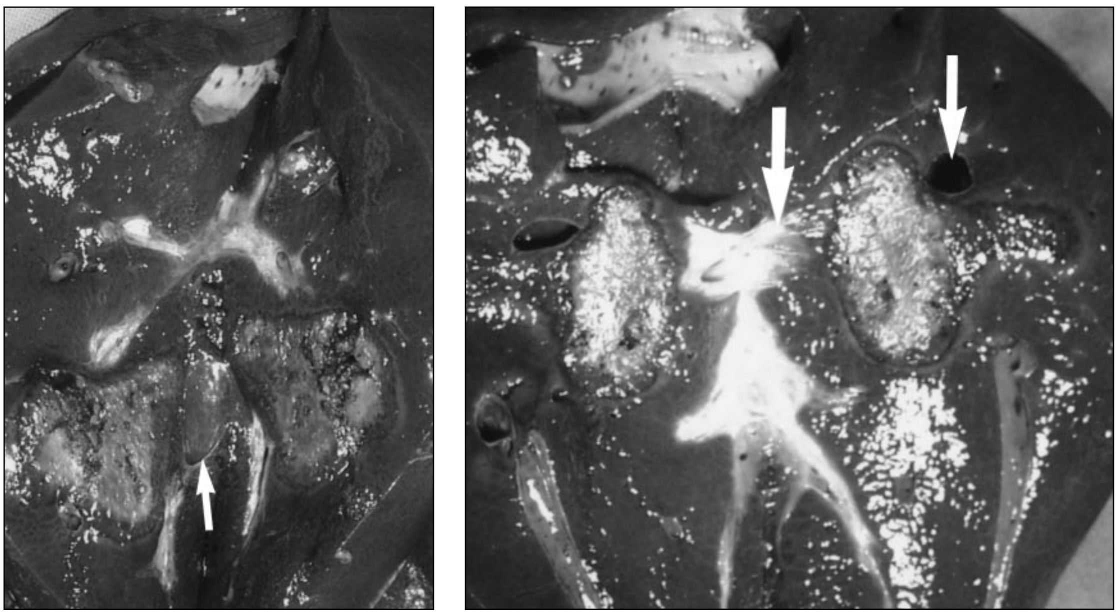
cm in diameter. These spots corresponded to the extremities of the expandable hook electrodes (Fig. 3) and were too small to produce confluent elements forming a single larger lesion, as was the case during the other sessions with the expandable needle (Fig. 4). These four attempts were not taken into account for statistical analysis. In three of these four cases, electrodes were centrally located and close to large vessels. Regardless of which radiofrequency system was used, large vessels adjacent to or within the radiofrequency delivery area were spared. The radiofrequency thermal lesions molded themselves to the shape of the vessels (Fig. 3), as predicted by the heat-sink effect. On the other hand, small vessels of less than 2–3 mm in diameter that were inside the radiofrequency delivery area were obstructed by clots (Fig. 4) regardless of which system was used.

Blood Loss

Blood loss was always less than 7 g for both needles except for one puncture in each group that was associated with a blood loss of 20 g for the cooled-tip needle and 10.4 g for the expandable needle. The median value of blood loss evaluated by weighing the gauze swab was 3.50 g for the triple-cluster cooled-tip needle and 2.62 g for the expandable needle; there was no statistically significant difference between the two groups ($p = 0.06$).

Discussion

Thermal energy sources such as radiofrequency [12], laser [20], or microwaves [21]



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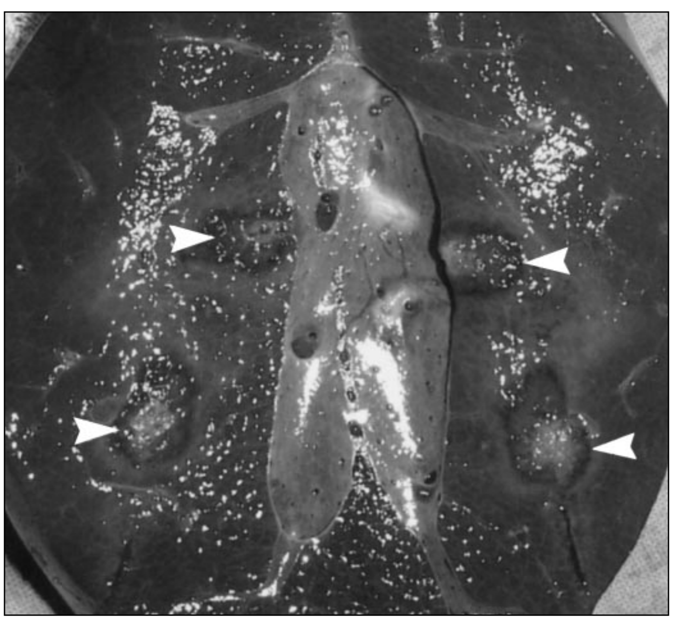

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Fig. 3.—Radiofrequency lesions located close to large vessels.
A, Photograph shows evidence of heat-sink effect. Lesion induced with cooled-tip needle was partially modified in shape by adjacent large hepatic vein (*arrow*).
B, Photograph shows evidence of heat-sink effect. Lesion induced with expandable needle molded around large vessels (*arrows*), which are responsible for its irregular shape.
C, Photograph shows radiofrequency ablation induced only four small areas of tissue destruction (*arrowheads*) at periphery of large hepatic vein. Expandable system failed to induce a large lesion in this case.

have been introduced as minimally invasive methods for the destruction of primary or secondary hepatic tumors. Successful tumor ablation with these techniques is achieved when the tumor is completely destroyed by heat. The ideal tool for this purpose would create, during one session, an area of destruction from 0.5 to 1 cm larger than the targeted tumor in a manner akin to surgical margins. On the basis of a 3-cm thermal injury induced with each radiofrequency application, Dodd et al. [22] reported that tumors less than 2 cm can be treated during one radiofrequency application, tumors that range from 2 to 3 cm required six overlapping ablations, and tumors greater than 3 cm require at least 12 overlapping ablations. Furthermore, even if the multiplication of treatment positions is an accepted drawback, the technical prowess involved in accurately placing the needles is a formidable challenge in clinical practice, and operators are prone to errors in placement when multiple positioning of probes or fibers is used to achieve complete tumor destruction. Multiplications of treatment positions have been applied in most of the published series for all but the smallest tumors [7, 12, 15, 23]. Consequently, the maximal size of the area of tissue destruction that can be induced by a single treatment is of paramount importance because it directly determines the maximal tumor size that can be treated during a single application, the number of applications required for large tumors, and the likelihood of complete tumor treatment.

In our experience, the cooled-tip needle clearly induced significantly larger lesions than the expandable needle in all the experiments. This difference can probably be attributed to delivery of power exceeding 100 W, and up to 200 W, throughout the procedure. In contrast, the expandable needle generator delivered its maximum output of 50 W during the initial treatment only before the temperature rose to the desired threshold, because the mean tissue temperature was limited to 95°C to avoid boiling and charring. Even if part of the energy delivered with the cooled-tip needle generator was reabsorbed by the cooling liquid, the total amount of energy delivered to the tissue with the cooled-tip needle was probably much greater than that with the expandable needle system given the disparity in lesion size, although this factor is difficult to quantify. However, the sizes of and the differences in size among the radiofrequency lesions between the two systems that we report here are valid for healthy liver, but these values could be different when treating liver tumors because tumors have various patterns of vascularization and because of underlying liver diseases such as cirrhosis, both of which modify energy deposition [6].

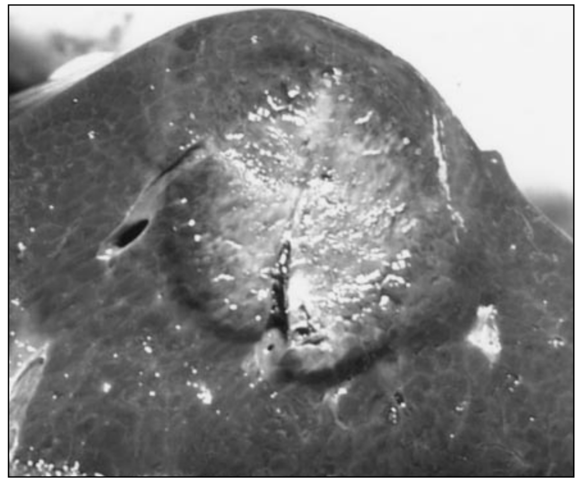

Fig. 4.—Photograph of round lesion, induced with expandable needle system, in liver parenchyma shows small clotted portal vein branch runs through lesion and patent larger vessels at periphery.

Lesions induced with the cooled-tip needle were larger than those induced with the expandable needle; however, lesions induced with the expandable needle were significantly more reproducible in size in vitro than those induced with the cooled-tip needle. Indeed, coefficients of variations in vitro were 10% and 17% for the expandable needle and the cooled-tip needle, respectively ($p = 0.007$). The difference in variability in vivo was not statistically significant. The higher in vivo variability in size for both techniques is explained by the heat-sink effect, whereby varying size and proximity of vessels alter the size and shape of the lesion induced by ablation. The heat-sink effect has been previously described for radiofrequency ablation [24]. The four sessions during which the expandable needle was able to induce only small lesions at the tips of the expandable electrodes showed that the expandable needle system is more sensitive to vascular flow and heat sink than the cooled-tip system. Again, the lower amount of energy delivered in the liver is probably a valid explanation. Indeed, a lower rate of energy output from the generator promotes heat sink. However, these four lesions were not included in the analysis because they probably would have been depicted in clinical practice when using image monitoring. Nevertheless, the expandable needle system had four failures and the cooled-tip needle did not have any failures; both systems were used in the same experimental conditions—namely, without imaging guidance.

Radiofrequency lesions obtained with the expandable needle were more spheric than those obtained with the cooled-tip needle, which is shown by the significant differences between the ratio of the longest axis to shortest axis. This more spheric shape can be explained by the geometry of the two systems. Indeed, the cooled-tip needle cluster is made of three 2.5-cm active electrodes that are 0.5 cm apart, thus producing a more oval shape than that of the 3-cm umbrella of the expandable needle. The cluster needle was probably designed to allow insertion of the cluster needle through the intercostal space rather than to create a spheric area of destruction. Regardless of the reasons for the design choice, a spheric lesion could be an advantage when treating hepatic tumors because these tumors are usually spheric.

Blood loss differed considerably from one puncture to another, regardless of which needle was used, but blood loss differed without statistical difference from one needle to another. Blood loss was less than 7 g except for two punctures, in which blood loss was more than 10 g possibly because of transgression of a large vessel in the needle path on the way to the targeted treatment site. Although the amount of blood loss was low, we have tried to completely eliminate blood loss since performing this study by applying full-power radiofrequency for 2 min at the puncture site on the liver capsule when retrieving the needle. Because 10 of 10 attempts have proved efficient, this technique could be an alternative solution in clinical practice for the treatment of patients with coagulation disorders, but it should be noted that this maneuver is painful to patients who were under conscious sedation. Ablation involving the hepatic capsule has been associated with more intraprocedural pain [25].

Disparities among the different ablation systems marketed at any one time present a problematic challenge to routine clinical applications and rigorous scientific evaluation. However, a comparison of different techniques and systems has potentially broad clinical merit and may assist in planning ablations. Every tumor should be evaluated before radiofrequency ablation in terms of its proximity to large vessels, proximity to vital structures, and size plus the margin. Preprocedural knowledge of the strengths and weaknesses of each ablation system should translate into more appropriate stratification of the relative importance of ablation factors such as thermal lesion size, uniformity, and predictability. Other technical differences between the two systems (expandable needle and cooled-tip needle) should be considered before choosing a system for a particular tumor. The expandable needle is slightly more stable because its arrays hold the probe precisely in place when expanded. The cooled-tip needle probe is occasionally prone to movement during treatment sessions, especially when treating tumors in the dome of the liver with a subcostal approach. We have seen this anecdotally in two cases, one of which was successfully treated subsequently with the expandable needle.

Although the expandable needle with four arrays powered by a 50-W generator induces a smaller lesion than the triple-cluster cooled-tip needle, the expandable needle produces lesions that are more spheric than those produced by the cooled-tip needle. New designs of the expandable needle system have been released recently, including systems with more arrays, with arrays at different spatial locations, and with a more powerful generator, to try to improve weaknesses in the currently tested system—namely, the possibility of creating only small areas of destruction at the tip of the electrodes. Further comparison studies are needed and may have broad clinical implications. Better prediction of the technical outcome should provide a higher chance of successful clinical outcome.

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