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INTERVENTIONAL

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Electrodes and multiple electrode systems for radiofrequency ablation: a proposal for updated terminology

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Abstract Research on technology for soft tissue radiofrequency (RF) ablation is ever advancing. A recent proposal to standardise terminology of RF electrodes only deals with the most frequently used commercial electrodes. The aim of this study was to develop a logical, versatile and unequivocal terminology to describe present and future RF electrodes and multiple electrode systems. We have carried out a PubMed search for the period from January 1 1990 to July 1 2004 in seven languages and contacted the six major companies that produce commercial RF electrodes for use in clinic. In a first step, names have been defined for the five existing basic designs of single-shaft electrode. These names had to be unequivocal, descriptive of the electrode's main working principle and as short as possible. In a second step, these basic names have been used as building blocks to describe the single-shaft electrodes in combination designs. In a third step, using the same principles, a logical terminology has been developed for multiple electrode systems, defined as the combined use of more than one single-shaft RF electrode. Five basic electrode designs were identified and defined: plain, cooled, expandable, wet and bipolar electrodes. Combination designs included cooled–wet, expandable–wet, bipolar–wet, bipolar–cooled, bipolar–expandable and bipolar–cooled–wet electrodes. Multiple electrode systems could be characterised by describing several features: the number of electrodes that were used (dual, triple, ...), the electric mode (monopolar or bipolar), the activation mode (consecutive, simultaneous or switching), the site of the inserted electrodes (monofocal or multifocal), and the type of single shaft electrodes that were used. In this terminology, the naming of the basic electrode designs has been based on objective criteria. The short and unequivocal names of the basic designs can easily be combined to describe current and future combination electrodes. This terminology provides an exact and complete description of the versatile novel multiple electrode systems.

Keywords Radiofrequency ablation · Liver · Kidney · Soft tissues

Introduction

The development of novel and ingenious electrodes for soft tissue (such as liver and kidney) radiofrequency ablation (RFA) is expanding rapidly. Multiple names to describe RF electrodes are being utilised. A proposal to address this semantic confusion was recently published by the IWGIGTA (International Working Group on Image-Guided Tumor Ablation) [1]. It described most of the commercial electrodes that were available at that moment. Since this publication, many new commercial and experimental electrodes, as well as several "multiple electrode systems" have been introduced.

The aim of this article is to update the existing classification and to present a logical and easily adoptable terminology for the generic classification of all RF electrodes and multiple electrode systems.

Materials and methods

We carried out a PubMed search of the world literature for the period from January 1, 1990 to July 1, 2004 using the keywords (radiofrequency, radio-frequency or radio frequency) and (liver or hepatic or hepatocellular) on articles written in English, French, German, Italian, Spanish, Danish and Dutch. In addition, all abstract supplements from the same period published in *Radiology, American Journal of Radiology*, *Journal of Vascular and Interventional Radiology*, *European Radiology*, and *Surgical Endoscopy* were searched manually. Relevant papers were also identified from the reference lists of the papers previously obtained through the search and from abstracts of recent international meetings. Further, the six major companies that produce commercial RF electrodes were contacted: Valleylab, (formerly Radionics Boulder, CO, USA); RITA Medical Systems (Mountain View, CA, USA); Boston Scientific (formerly Radiotherapeutics; Natick, MA, USA); Berchtold (Tuttlingen, Germany); Invatec (Roncadelle, Italy); and Celon AG Medical Instruments (Teltow, Germany) [2–7].

For each basic electrode design, a generic name has been defined which had to be unequivocal, descriptive of the electrode's main working principle and as concise as possible. In a second step, these basic names have been combined to describe the combination electrode designs. In a third step, a logical description of the combined use of more than one RF electrode in multiple electrode systems has been worked out.

Results

Single-shaft electrodes

Basic designs

Plain electrodes The first experiments with RF ablation on liver tissue were performed with *plain* metal electrodes (Table 1, Figs. 1, 2, 3). The ablation diameter was very limited, due to a rapid rise in electric impedance with current shut-off. To overcome size limitations in RFA, modified single-shaft electrodes have been developed and tested since 1994. Four approaches have been followed: internal cooling (cooled electrodes), spreading RF current over a larger volume and enlargement of the electrode–tissue interface (expandable electrodes), saline perfusion through the electrode into the tissue (wet electrodes) and bipolar design (bipolar electrodes) [8, 9].

Cooled electrode The *cooled* electrode [10–15] is a hollow electrode that contains an inner cannula, dividing the space inside the electrode into a concentric outer and inner lumen. The inner lumen is used to deliver a chilled fluid to the tip of the electrode and the outer returns the fluid to an external collection unit. The fluid does not leave the elec-

Table 1 Single-shaft radiofrequency electrodes, basic designs: proposed terminology

Current proposal	IWGIGTA proposal	Other synonyms in literature
Plain	–	
Cooled	Internally cooled	Perfusion, closed perfusion, perfused, internally cooled-tip
Single cooled	Single internally cooled	
Cluster cooled	Cluster internally cooled	Array, clustered internally cooled, triple cooled
Expandable	Multitined expandable	Retractable, umbrella, Christmas tree, multiple hooked, array, anchor, multi-probe needle
Multitined expandable	Multitined expandable	Retractable, umbrella, Christmas tree, multiple hooked, array, anchor, multi-probe needle
Coiled expandable	–	
Bipolar	–	
Wet	Perfusion	Liquid, virtual, saline, saline-enhanced, saline-augmented, saline infusion, perfused, open perfused, saline solution perfusion

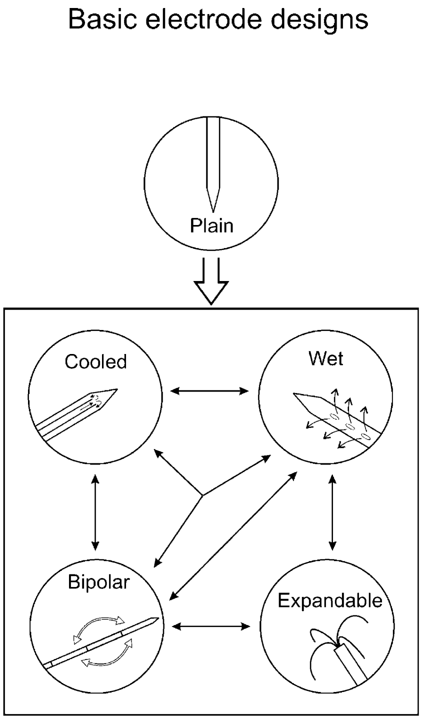


Fig. 1 Five basic designs of RF ablation electrodes (plain, cooled, wet, expandable and bipolar) have led to the development of six combination designs (cooled–wet, expandable–wet, bipolar–wet, bipolar–cooled, bipolar–expandable and bipolar–cooled–wet)

trode. This way, the tip is internally cooled to a temperature below 25°C to prevent charring of the tissue immediately adjacent to the tip. In a *cluster cooled* electrode [16], three parallel cooled electrodes have been mounted on the same shaft in a triangular fashion with an inter-electrode distance of 5 mm. The electrodes are activated simultaneously. The larger contact surface allows higher current intensity with less charring around the tip and therefore larger thermal lesions than with single cooled electrodes [16].

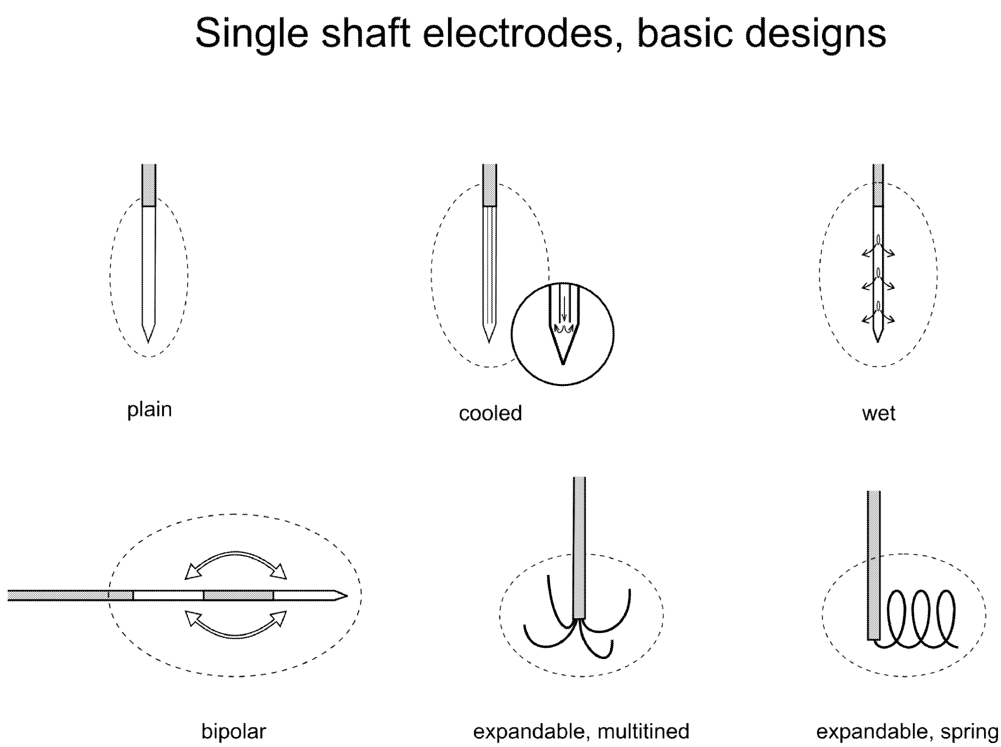
Expandable electrodes An expandable electrode is inserted as a straight insulated needle into the tissue. Once in the desired position, the active electrode is deployed from the hollow shaft of the probe. Two types exist: the *multitined* type and the *coiled* type.

Multitined electrodes [17] are an array of 4–12 curved electrode tines ("prongs") that are deployed from the hollow needle tip in an umbrella-like or Christmas tree-like fashion. The coagulation shape follows the configuration of the deployed prongs. The power is distributed over a wider surface area, therefore current density and the chance of charring decrease.

A *coiled* electrode has a spring that leaves the tip and that is deployed perpendicularly to the shaft [18].

Wet electrode The *wet* electrode [19, 20] (Figs. 1, 2, 3, and 4) consists of a hollow electrode with one or more holes at

Fig. 2 Single shaft electrodes: basic designs



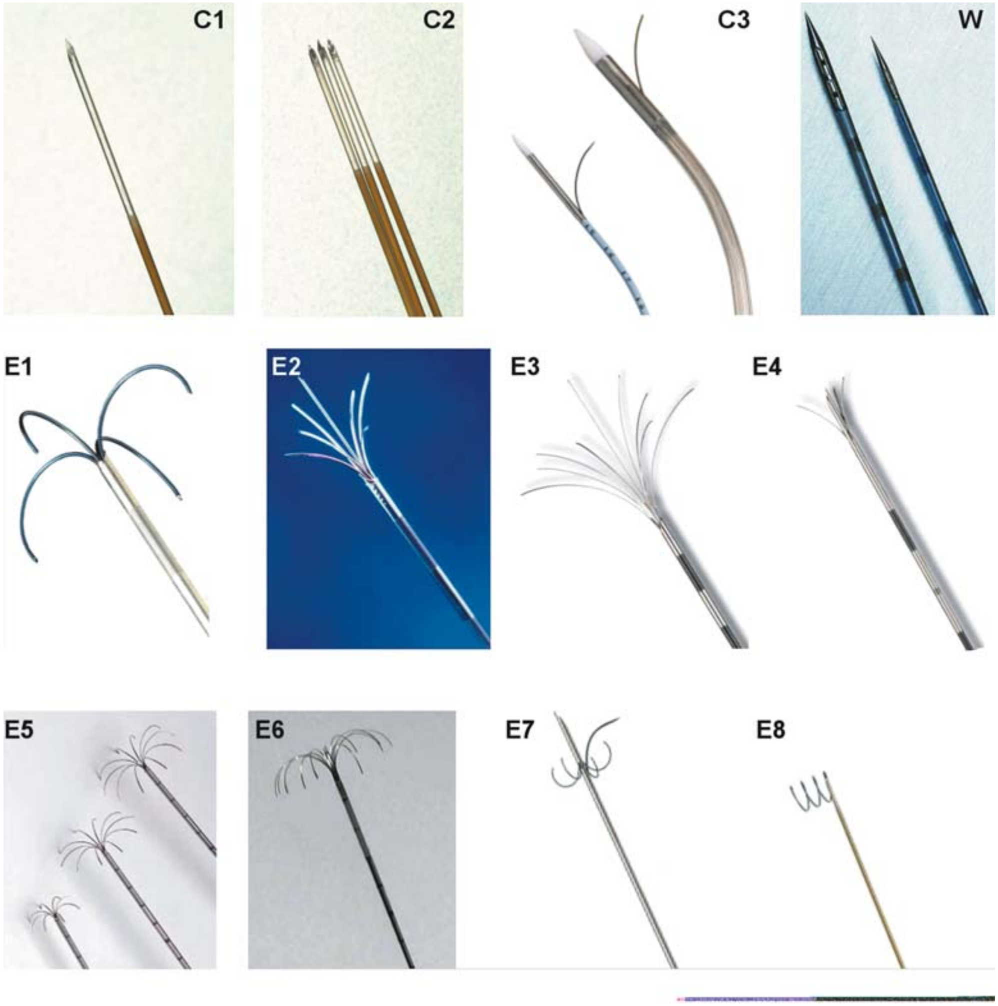


Fig. 3 Examples of commercial electrodes with a basic design. *C(ooled) 1* Radionics Cool-tip RF single 3-cm tip; *C(ooled) 2* Radionics Cool-tip RF cluster; *C(ooled) 3* Convatec MIRAS IOC and Convatec MIRAS LC (*top* to *bottom*); *W(et)* Berchtold HiTT 1-cm tip/1.2 mm diameter and 1.5-cm tip/2 mm diameter; *E(xpandable) 1* RITA model 30; *E(xpandable) 2* RITA model 70; *E(xpandable) 3* RITA model 90/StarBurst XL; *E(xpandable) 4* RITA StarBurst SD; *E(xpandable) 5* Boston Scientific LeVeen 2, 3, and 3.5 cm; *E(xpandable) 6* Boston Scientific LeVeen 4 cm; *E(xpandable) 7* Invatec MIRAS LN; *E(xpandable) 8* Invatec MIRAS RC

the uninsulated distal end through which an isotonic or hypertonic saline solution is infused into the tissue. The infused saline improves thermal and electrical tissue conductivity, which allows for a greater than 10-fold increase in power deposition compared to a plain electrode [21].

Bipolar electrodes In *bipolar* electrodes, both electrodes are incorporated proximally and distally on the same neutral probe with a variable distance between them [22, 23]. The electric current flows between the two electrodes, and no grounding pad is used.

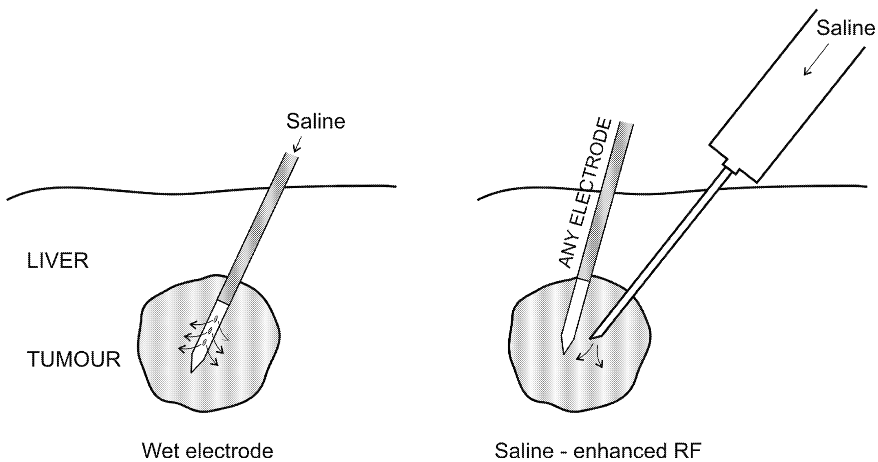


Fig. 4 Wet electrode-RF ablation versus saline-enhanced RF ablation

Table 2 Single-shaft radiofrequency electrodes, combination designs: proposed terminology

Current proposal	Synonyms in literature
Double combination designs	
Cooled–wet	Perfusion, perfused–cooled, wet–cooled, open–perfused
Expandable–wet	Perfusion
Bipolar–wet	
Bipolar–cooled	
Bipolar–expandable	Bipolar
Bipolar–cooled–wet	
Triple combination designs	
Bipolar–cooled–wet	Bipolar perfused–cooled

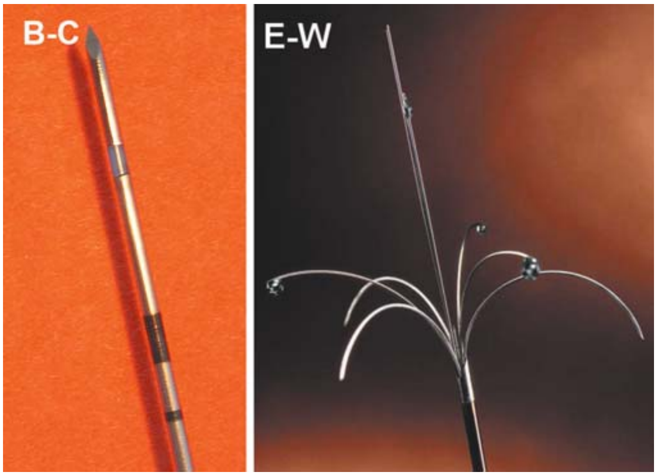


Fig. 6 Examples of commercial electrodes with a combination design. *B(ipolar)–C(ooled)* CelonProSurge 150T30 electrode, *E(xpandable)–W(et)* RITA model 100/StarBurst XLi 70

Double combination electrode designs

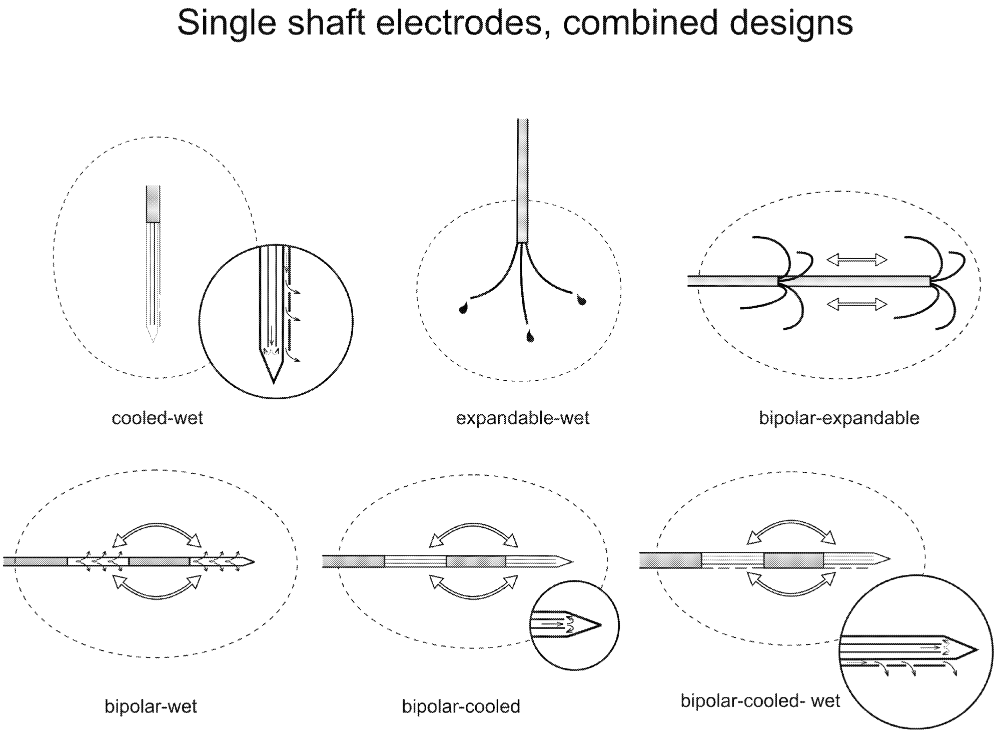
Cooled–wet electrode The *cooled–wet* electrode allows continuous infusion of interstitial saline along the cooled electrode (Table 2, Figs. 1, 5, 6). The cooled–wet electrode yields larger ablation zones than both the wet and the cooled electrode separately [24, 25].

Expandable–wet The *expandable–wet* electrode, which unites features of both techniques, is more effective than the wet or expandable electrode separately in an experimental setting [26, 27].

Bipolar–wet electrode A *bipolar–wet* electrode consists of an insulated shaft with two electrodes, connected in a bipolar fashion and separated by an insulated portion. Saline flows into the tissue at both active parts [28].

Bipolar–cooled electrode A *bipolar–cooled* electrode consists of an internally cooled and insulated shaft with two exposed electrode parts, connected in a bipolar fashion and separated by an insulated portion [22].

Fig. 5 Single shaft electrodes: combination designs



Bipolar–expandable electrode A *bipolar–expandable* electrode consists of two expandable electrodes that are incorporated in parallel into one shaft [29]. Current flows between the two expanded parts.

Triple combination electrode designs

Bipolar–cooled–wet electrode A bipolar–cooled–wet electrode consists of a cooled–wet electrode with a second, more proximal exposed electrode part, connected in a bipolar fashion and separated by an insulated portion [30] (Table 2; Figs. 1, 5).

Multiple electrode systems

Multiple electrode systems are defined as the combined use of more than one single-shaft electrode (Table 3; Figs. 7, 8). Their use can be described according to the number of electrodes used, electric mode, activation mode, and location of the inserted electrodes. Multiple electrode systems have been built with many types of electrodes. The number of possible combinations using these different variables is infinite.

Table 3 Multiple electrode systems: proposed terminology

Current proposal	Synonyms in literature
According to number	
Dual, triple, quadruple, ...	
According to electric mode	
Monopolar	
Bipolar	
According to activation mode	
Consecutive	Sequential
Simultaneous	
Switching	Multipolar, sequential, alternative, alternating
According to site of insertion	
Unifocal	
Multifocal	
According to electrodes	
Plain electrode system	Multiprobe array, bipolar, multibipolar, multielectrode
Wet electrode system	Bipolar saline-enhanced
Cooled electrode system	
Expandable electrode system	
Cooled–wet electrode system	
Bipolar–cooled electrode system	Multipolar

Number of electrodes used

A multiple electrode system can consist of two (*dual*), three (*triple*), four (quadruple), or more electrodes.

Electric mode

A multiple electrode system can be used in the *monopolar* mode [29, 31–35]. The electric current flows from all the electrodes that have the same polarity towards the grounding pad. Alternatively, in the *bipolar* mode [36–42], the current flows between two parallel inserted electrodes or groups of electrodes. The inaccurate term "bipolar RFA" should be avoided, because it can cause confusion. Instead, authors should clearly describe whether they use a bipolar *single-shaft electrode* or whether they use the bipolar *mode* between two (or more) *parallel* inserted electrodes *in multiple electrode systems*.

Activation mode

Multiple electrodes can be activated *consecutively* [31, 34, 35]: the second electrode is activated after completion of the session of the first electrode etc. They can also be activated *simultaneously* [29, 32–34], or in a rapid *switching* mode using a switch box [29, 34].

Insertion site of the electrodes

Usually, the multiple electrodes are inserted in the same part of the organ to treat the same tumour (*monofocal* RFA). Alternatively, two (or more) (groups of) electrodes can be inserted in a different part of the organ, to obtain a simultaneous treatment at different locations (*multifocal* RFA, e.g. *bifocal* or *trifocal* RFA) [43]. For multifocal RFA, the interposition of a switch box between electrodes and generator is necessary. This switch box is usually programmed to distribute the current in an alternating mode to the different locations, but it can be programmed in any activation mode as well as in any electric mode (Mulier, unpublished data).

Types of electrodes used in multiple electrode systems

Multiple electrode systems can be made with any of the available single-shaft electrodes. The following systems have been described in the literature.

A *plain electrode system* consists of two or more plain electrodes that are inserted in a parallel way into the tissue. Two electrodes can be arranged in a bipolar mode [29, 36], or current can be applied simultaneously to multiple electrodes in a monopolar mode [29, 31, 32]. A third option is

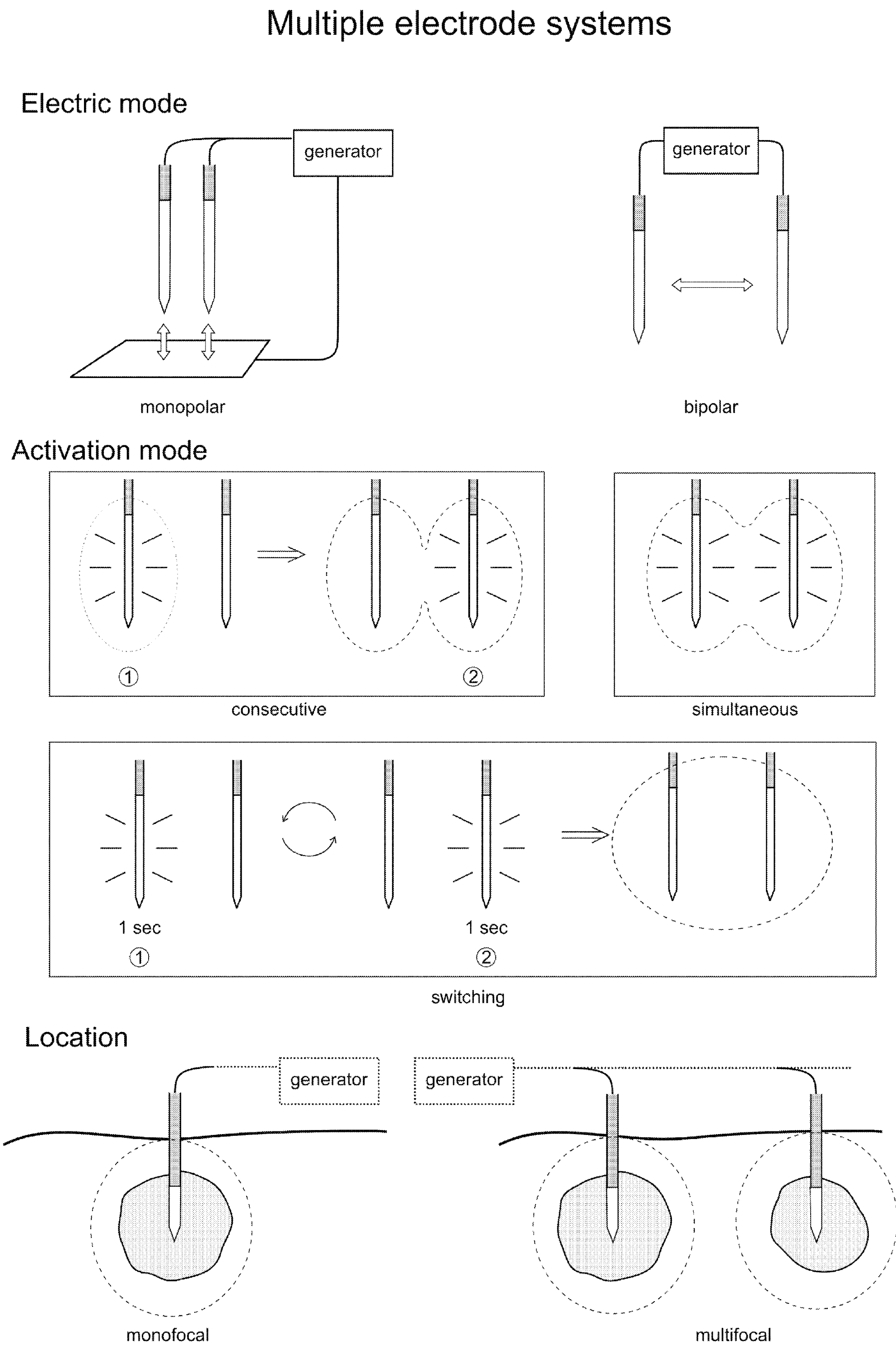


Fig. 7 Multiple electrode systems: they can be characterised by the number of electrodes used (not shown), the electric mode (example with two plain electrodes), activation mode (example with two plain electrodes), site of insertion (example with one plain electrode at each location) and (not shown) type of single shaft electrodes used

to insert multiple plain electrodes in a parallel way, half of which are connected to the positive pole and half of which are connected to the negative pole [37, 38, 42].

Similarly, by inserting two or more parallel electrodes of the same kind, a *wet electrode system* [39, 40, 44], a *cooled electrode system* [33, 34], an *expandable electrode system* [29, 35, 41, 45], a *cooled–wet electrode system* [30, 44] and a *bipolar–cooled electrode system* [7] have been described.

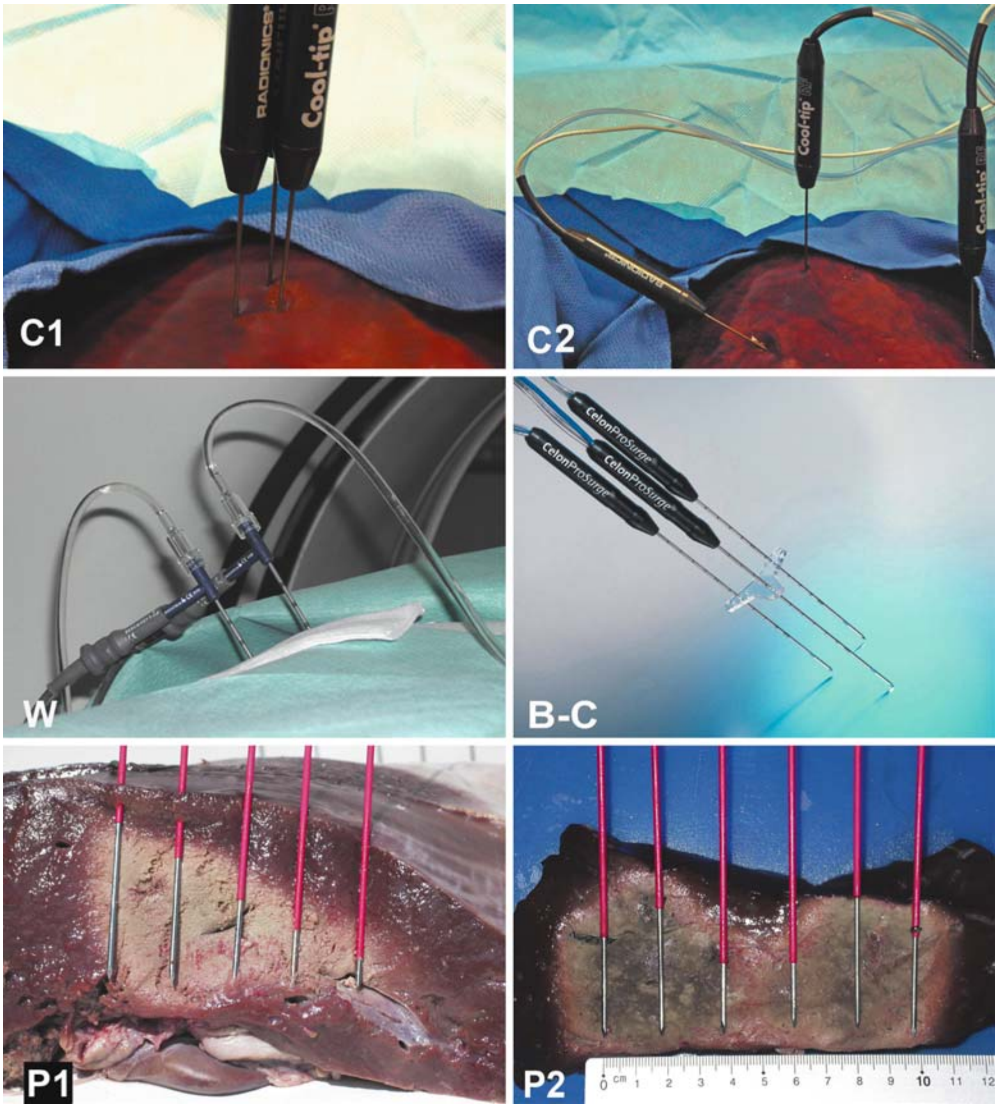


Fig. 8 Examples of multiple electrode systems. *C(ooled) 1* Three Radionics Cool-tip RF single 3-cm tip with monofocal insertion in the switching and monopolar mode to treat 3 one large tumour; *C(ooled) 2* three Radionics Cool-tip RF single 3-cm tip with multifocal insertion in the switching and monopolar mode to treat three different sites at the same time; *W(et)* two Berchtold HiTT electrodes with monofocal insertion in the bipolar mode to treat one large tumour; *B(ipolar)–C (ooled)* three CelonProSurge 150T40 electrodes that will be used with monofocal insertion in the switching and bipolar mode to treat one large tumour; *P(lain) 1* two rows (only one shown) of five plain metal electrodes of uneven lengths, spaced apart 2 cm and activated in a bipolar and simultaneous mode in ex vivo beef liver; note the triangular shape of the coagulation that closely matches the distribution of the unexposed parts of the electrodes; *P(lain) 2* two rows (only one shown) of six plain metal electrodes of uneven lengths, spaced apart 2 cm and activated in a bipolar mode in ex vivo beef liver; the three pairs of electrodes left and the three pairs right have been activated consecutively. Note the bilobar shape of the coagulation that closely matches the distribution of the unexposed parts of the electrodes

Saline-enhanced RF ablation

In *saline-enhanced RF ablation* [46], saline is directly injected into the tissue near the electrode tip [47–50]. The injection needle is not incorporated into the electrode, in contrast to the wet electrode (Fig. 4, Table 4). Saline-enhanced RF ablation can be performed in combination with any of the existing electrodes and multiple electrode systems. Saline-enhancement has been reported for *cooled* electrodes [47, 49–51], *multiple plain* electrodes [46] and *expandable* electrodes [48]. Saline is usually injected as a bolus prior to RF ablation [47, 49, 50], in contrast to the wet electrode, with which usually a continuous infusion after a pre-RF ablation bolus is used.

Reports on saline-enhanced RF ablation should specify details on the injection method.

Table 4 Wet electrode-RF ablation versus saline-enhanced RF ablation

	Wet electrode RF ablation	Saline-enhanced RF ablation
Method of saline instillation	Saline infused through electrode	Saline injected through separate needle
Site of saline exit	Side-holes of electrode	Tip of separate needle
Device	Dedicated electrode	Saline injection can be combined with any electrode
Timing of saline instillation	Usually bolus pre-RF ablation plus continuous infusion during RF ablation	Usually bolus pre-RF ablation

Discussion

Research and clinical application of soft tissue RF ablation is booming. Proposals have recently been launched to standardise reporting on RF ablation. A recent paper from the IWGIGTA (International Working Group on Image-Guided Tumor Ablation) proposes standardised terms for various aspects in the broad field of image-guided tumour destruction [1]. Other papers focused on standardised reporting of one specific aspect of RF ablation, such as RF ablation treatment protocols [52], size and geometry of RF ablation lesions [18] and severity of complications [53, 54]. All these efforts at standardisation are crucial to improve scientific communication on RFA.

The IWGIGTA proposal described most of the commercial electrodes that were available at that moment (Table 1). It did not yet cover the many new commercial and experimental electrodes, as well as several "multiple electrode systems" that have been introduced since. The aim of this article is to update and adapt the existing classification and to present a logical and easily adoptable terminology for the generic classification of all RF electrodes and multiple electrode systems.

At present, the naming of many new experimental and commercial electrode types is much influenced by *subjective factors*: personal preferences of the inventors or major users, or fancy names for marketing purposes. In order to obtain a logical terminology for RF electrodes that was scientific and acceptable to all, we first developed *objective criteria* that had to be fulfilled to name the basic electrode designs. These names had to be unequivocal, descriptive of the electrode's main working principle and as short as possible. A short name was crucial to be able to combine these names to describe the combination designs in a second step.

As a logical consequence of these objective criteria, two of the terms for the basic designs of the IWGIGTA proposal had to be adapted.

In the present terminology proposal, the term *wet electrode* replaces "perfusion electrode". The term "perfusion electrode" is still equivocal: this name is currently being used in the literature for both the *wet electrode*, which is perfused with saline which leaves the tip through small holes ("open perfusion electrode" [44], or "externally perfused electrode" [55]); and for the *cooled electrode*, which is perfused with water which does not leave the electrode ("closed perfusion electrode" [56], or "internally perfused electrode" [55]). Further, the IWGIGTA classification uses the same term "perfusion electrode" for both the *wet* and the *cooled–wet* electrode, which clearly have a different design and efficacy [24, 25, 57].

The term we propose, *wet electrode*, is short, unequivocal, descriptive of the electrode's main working principle and used by several pioneering authors in this field [21, 24, 25, 58–60]. It is currently being used as part of the name to describe several experimental electrodes and multiple electrode systems [24, 25, 27, 44, 57, 60].

The term "internally cooled" electrode from the IWGIGTA classification has been shortened to *cooled* electrode, which is equally clear (as an externally cooled electrode does not exist) but shorter and easier to combine in names such as *cooled–wet*; *bipolar–cooled* etc.

The system of short unequivocal names for the basic electrode designs allows the easy introduction of combined names for electrodes with a *combination design*, even for future electrodes that have yet to be designed. Conversely, the clarity of the combined names facilitates the understanding of the design.

The introduction of the concept of *multiple electrode systems*, that consist of the combination of more than one single-shaft electrode and that can be used in many modes, was essential to cover this most recent and promising evolution in RF ablation technology. The names of these modes have been standardised too. The unequivocal term *switching* mode replaces the term "sequential", which has been used as a synonym for both the *alternating* and the *consecutive* mode.

Due to superficial similarities, saline-enhanced RF ablation and wet electrode-mediated RF ablation are often confounded. It is hoped that the present definition, the table and the illustration can help to clearly distinguish these different technologies.

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References

1. Goldberg SN, Charboneau JW, Dodd GD III, Dupuy DE, Gervais DA, Gillams AR, Kane RA, Lee FT Jr, Livraghi T, McGahan JP, Rhim H, Silverman SG, Solbiati L, Vogl TJ, Wood BJ (2003) Image-guided tumor ablation: proposal for standardization of terms and reporting criteria. Radiology 228:335–345
2. http://www.radionics.com/default-ab.shtml. Accessed 4 Feb 2004
3. http://www.ritamedical.com/. Accessed 4 Feb 2004
4. http://www.bostonscientific.com/. Accessed 4 Feb 2004
5. http://www.berchtold.de/2/main2.htm. Accessed 4 Feb 2004
6. http://www.invatec.it/1024/index1024.htm. Accessed 4 Feb 2004
7. http://www.celon.com/htdocs/1tech/efset1.htm. Accessed 30 June 2004
8. Denys AL, De Baere T, Kuoch V, Dupas B, Chevallier P, Madoff DC, Schnyder P, Doenz F (2003) Radio-frequency tissue ablation of the liver: in vivo and ex vivo experiments with four different systems. Eur Radiol 13:2346–2352

9. Pereira PL, Trubenbach J, Schenk M, Subke J, Kroeber S, Schaefer I, Remy CT, Schmidt D, Brieger J, Claussen CD (2004) Radiofrequency ablation: in vivo comparison of four commercially available devices in pig livers. Radiology 232:482–490
10. De Baere T, Elias D, Ducreux M, Dromain C, Kuoch V, El Din MG, Sobotka A, Lasser P, Roche A (1999) Percutaneous radiofrequency ablation of hepatic metastases. Preliminary experience. Gastroenterol Clin Biol 23:1128–1133
11. Goldberg SN, Gazelle GS, Solbiati L, Rittman WJ, Mueller PR (1996) Radiofrequency tissue ablation: increased lesion diameter with a perfusion electrode. Acad Radiol 3:636–644
12. Lencioni R, Goletti O, Armillotta N, Paolicchi A, Moretti M, Cioni D, Donati F, Cicorelli A, Ricci S, Carrai M, Conte PF, Cavina E, Bartolozzi C (1998) Radio-frequency thermal ablation of liver metastases with a cooled-tip electrode needle: results of a pilot clinical trial. Eur Radiol 8:1205–1211
13. Lorentzen T (1996) A cooled needle electrode for radiofrequency tissue ablation: thermodynamic aspects of improved performance compared with conventional needle design. Acad Radiol 3:556–563
14. Solbiati L, Goldberg SN, Ierace T, Livraghi T, Meloni F, Dellanoce M, Sironi S, Gazelle GS (1997) Hepatic metastases: percutaneous radio-frequency ablation with cooled-tip electrodes. Radiology 205:367–373
15. Trübenbach J, Huppert PE, Pereira PL, Ruck P, Claussen CD (1997) Radiofrequency ablation of the liver in vitro: increasing the efficacy by perfusion probes. RoFo Fortschr Geb Rontgenstrahlen Neuen Bildgeb Verfahr 167:633–637
16. Goldberg SN, Solbiati L, Hahn PF, Cosman E, Conrad JE, Fogle R, Gazelle GS (1998) Large-volume tissue ablation with radio frequency by using a clustered, internally cooled electrode technique: laboratory and clinical experience in liver metastases. Radiology 209:371–379
17. Le Veen RF, Fox RL, Schneider PD, Hinrichs S (1996) Large volume porcine liver ablation with the use of a percutaneous expandable electrosurgical probe. J Vasc Interv Radiol 7(1, part 2):217–218
18. Mulier S, Ni Y, Miao Y, Rosiere A, Khoury A, Marchal G, Michel L (2003) Size and geometry of hepatic radiofrequency lesions. Eur J Surg Oncol 29:867–878
19. Hoey MF, Mulier PM, Shake JG (1995) Intramural ablation using radiofrequency energy via screw-tip catheter and saline electrode. PACE 18(II):917
20. Livraghi T, Goldberg SN, Monti F, Bizzini A, Lazzaroni S, Meloni F, Pellicano S, Solbiati L, Gazelle GS (1997). Saline-enhanced radio-frequency tissue ablation in the treatment of liver metastases. Radiology 202:205–210
21. Leveillee RJ, Hoey MF (2003) Radiofrequency interstitial tissue ablation: wet electrode. J Endourol 17:563–577
22. Mack M, Straub R, Desinger K, Balzer JO, Zangos S, Vogl TJ (2000) MR guided interstitial bipolar RF thermometry (RFITT): in vitro evaluations and first clinical results. Radiology 217 (Suppl):539
23. Mack MG, Desinger K, Straub R, Stein T, Balzer JO, Vogl TJ (2002) MR-guided bipolar RF-thermotherapy (RFITT): in-vitro evaluations and first clinical results. Eur Radiol 12(Suppl 1):141
24. Ni Y, Miao Y, Marchal G (2003) Cooled-wet electrode. US Patent 6,514,251 B1, 4 Feb 2003. Priority date: August 14, 1998
25. Miao Y, Ni Y, Yu J, Marchal G (2000) A comparative study on validation of a novel cooled–wet electrode for radiofrequency ablation. Invest Radiol 35:438–444
26. Miao Y, Ni Y, Yu J, Marchal GJ (1999) Optimization of radiofrequency ablation by using an “expandable–wet” electrode: results of ex vivo experiment. Radiology 213:102
27. Miao Y, Ni Y, Yu J, Zhang H, Baert A, Marchal G (2001) An ex vivo study on radiofrequency tissue ablation: increased lesion size by using an “expandable–wet” electrode. Eur Radiol 11:1841–1847
28. Mulier P, Hoey M. Method and apparatus for creating a bi-polar virtual electrode used for the ablation of tissue. US Patent no 6238393 B1, May 29, 2001. Priority date July 6, 1999
29. Haemmerich D, Tungjitkusolmun S, Staelin ST, Lee FT Jr, Mahvi DM, Webster JG (2002) Finite-element analysis of hepatic multiple probe radio-frequency ablation. IEEE Trans Biomed Eng 49:836–842
30. Lee JM, Han JK, Kim SH, Lee JY, Kim DJ, Lee MW, Cho GG, Han CJ, Choi BI (2004) Saline-enhanced hepatic radiofrequency ablation using a perfused-cooled electrode: comparison of dual probe bipolar mode with monopolar and single probe bipolar modes. Korean J Radiol 5:121–127
31. Wright AS, Haemmerich DG, Chachati L, Webster JG, Mahvi DM, Lee FT (2002) Hepatic radiofrequency ablation with multiple active electrodes is superior to conventional overlapping technique in an ex vivo model. Radiology 225(Suppl):639
32. Goldberg SN, Gazelle GS, Dawson SL, Rittman WJ, Mueller PR, Rosenthal DI (1994) Radiofrequency tissue ablation using multiprobe arrays: greater tissue destruction than multiple probes operating alone. Radiology 193:S281
33. Gillams AR, Lees WR (2001) Optimisation of treatment strategy using cooled-tip radiofrequency electrodes in ex-vivo liver. Eur Radiol 11(Suppl A):171
34. Lee JM, Rhim H, Han JK, Youn BJ, Kim SH, Choi BI (2004) Dual-probe radiofrequency ablation: an in vitro experimental study in bovine liver. Invest Radiol 39:89–96
35. Shirato K, Morimoto M, Tomita N, Kokawa A, Sugimori K, Saito T, Tanaka K (2002) Hepatocellular carcinoma: percutaneous radiofrequency ablation using expandable needle electrodes and the double-insertion technique. Hepato-gastroenterology 49:1481–1483
36. Jones CD, McGahan JP, Gu W, Brock JM (1995) Percutaneous liver ablation using bipolar radiofrequency electrocautery. Radiology 197:140
37. Mulier S, Ni Y, Mulier P, Marchal G, Michel L (2003) Multi-bipolar electrode system. Patent application GB0318661A0, 8 Aug 2003
38. Mulier S, Ni Y, Mulier P, Marchal G, Michel L (2003) Linear radiofrequency coagulation. Patent application GB0324458A0, 21 Oct 2003
39. Burdio F, Guemes A, Burdio JM, Castiella T, De Gregorio MA, Lozano R, Livraghi T (1999) Hepatic lesion ablation with bipolar saline-enhanced radiofrequency in the audible spectrum. Acad Radiol 6:680–686

40. Burdio F, Guemes A, Burdio JM, Navarro A, Sousa R, Castiella T, Cruz I, Burzaco O, Lozano R (2003) Bipolar saline-enhanced electrode for radiofrequency ablation: results of experimental study of in vivo porcine liver. Radiology 229:447–456
41. Lee FT, Staelin ST, Haemmerich D, Tungjitkusolmun S, Johnson CD, Mahvi DM (2000) Bipolar RF produces larger zones of necrosis than conventional monopolar RF in pig livers. Radiology 217(Suppl):229
42. Gananadha S, Morris DL (2004) Novel in-line multielectrode radiofrequency ablation considerably reduces blood loss during liver resection in an animal model. ANZ J Surg 74:482–485
43. Lee FT, Haemmerich D, Wright AW, Mahvi DM, Sampson LA, Webster JG (2003) Multiple probe radiofrequency ablation: pilot study in an animal model. J Vasc Interv Radiol 14:1437–1442
44. Lee JM, Han JK, Kim SH, Sohn KL, Choi SH, Choi BI (2004) Bipolar radiofrequency ablation in ex vivo bovine liver with the open–perfused system versus the cooled–wet system. Eur Radiol 2004 Jul 10 [Epub ahead of print]
45. Xu H, Xie X, Lu M, Chen J, Yin X, Xu Z, Liu G (2004) Ultrasound-guided percutaneous thermal ablation of hepatocellular carcinoma using microwave and radiofrequency ablation. Clin Radiol 59:53–61
46. Solbiati L, Ierace T, Goldberg SN, Sironi S, Livraghi T, Fiocca R, Servadio G, Rizzatto G, Mueller PR, Del Maschio A, Gazelle GS (1997) Percutaneous US guided radiofrequency tissue ablation of liver metastases: treatment and follow up in 16 patients. Radiology 202:195–203
47. Lobo SM, Afzal KS, Ahmed M, Kruskal JB, Lenkinski RE, Goldberg SN (2004) Radiofrequency ablation: modeling the enhanced temperature response to adjuvant NaCl pretreatment. Radiology 230:175–182
48. Lubienski A, Wirth-Jaworski L, Hahn T, Bitsch R, Lubienski K, Dechow C, Kauffmann G, Düx M (2003) Tissue modulation during radiofrequency ablation in an experimental liver perfusion model. Eur Radiol 13(Suppl 2): S114
49. Kim YK, Lee JM, Kim SW, Kim CS (2003) Combined radiofrequency ablation and hot saline injection in rabbit liver. Invest Radiol 38:725–732
50. Lee JM, Kim YK, Lee YH, Kim SW, Li CA, Kim CS (2003) Percutaneous radiofrequency thermal ablation with hypertonic saline injection: in vivo study in a rabbit liver model. Korean J Radiol 4:27–34
51. Solbiati L, Goldberg SN, Livraghi T, Meloni F, Ierace T, Cova L (2000) Radiofrequency thermal ablation: increased treatment effect with saline pretreatment. Radiology 217(Suppl):607
52. Helton WS (2004) Minimizing complications with radiofrequency ablation for liver cancer: the importance of properly controlled clinical trials and standardized reporting. Ann Surg 239:459–463
53. Buscarini E, Buscarini L (2004) Radiofrequency thermal ablation with expandable needle of focal liver malignancies: complication report. Eur Radiol 14:31–37
54. Omary RA, Bettmann MA, Cardella JF, Bakal CW, Schwartzberg MS, Sacks D, Rholl KS, Meranze SG, Lewis CA; Society of Interventional Radiology Standards of Practice Committee (2003) Quality improvement guidelines for the reporting and archiving of interventional radiology procedures. J Vasc Interv Radiol 14(9 Pt 2):S293–S295
55. Kettenbach J, Blum M, Kilanowicz E, Schwaighofer SM, Lammer J (2004) Percutaneous radiofrequency-ablation of liver cell carcinoma: a current overview. Radiologe 44:330–338
56. Schmidt D, Trubenbach J, Konig CW, Brieger J, Duda S, Claussen CD, Pereira PL (2003) Radiofrequenzablation ex-vivo: Vergleich der Effektivität von impedance control mode versus manual control mode unter Verwendung einer geschlossen perfundierten Cluster-Ablationssonde. RoFo Fortschr Geb Rontgenstrahlen Neuen Bildgeb Verfahr 175:967–972
57. Ni Y, Miao Y, Mulier S, Yu J, Baert AL, Marchal G (2000) A novel 'cooled–wet' electrode for radiofrequency ablation. Eur Radiol 10:852–854
58. Miao Y, Ni Y, Mulier S, Yu J, De Wever I, Penninckx F, Baert AL, Marchal G (2000) Treatment of VX2 liver tumor in rabbits with "wet" electrode mediated radio-frequency ablation. Eur Radiol 10:188–194
59. Hänsler J, Witte A, Strobel D, Wein A, Bernatik T, Pavel M, Muller W, Hahn EG, Becker D (2003) Radio-frequency-ablation (RFA) with wet electrodes in the treatment of primary and secondary liver tumours. Ultraschall Med 24:27–33
60. Gangi A, Guth S, Imbert J (2003) Interest of radiofrequency liver tissue ablation with a bipolar–wet electrode. Eur Radiol 13(Suppl 1):477

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