Diagnostic and Interventional Imaging (2017) 98, 287—297

REVIEW / *Interventional imaging*

Microwave ablation of renal tumors: A narrative review of technical considerations and clinical results

F.H. Cornelis [a,b,*], **C. Marcelin** [b], **J.-C. Bernhard** [c]

[a] *Department of radiology, Tenon hospital, 4, rue de la Chine, 75020 Paris, France*
[b] *Department of radiology, Pellegrin hospital, place Amélie-Raba-Léon, 33076 Bordeaux, France*
[c] *Department of urology, Pellegrin hospital, place Amélie-Raba-Léon, 33076 Bordeaux, France*

KEYWORDS
Interventional imaging;
Renal ablation;
Microwave ablation;
Kidney;
Renal cancer

Abstract
Purpose: The purpose of this review was to identify the specific technical considerations to adequately perform microwave ablations (MWA) of renal tumors and analyze the currently available clinical results.
Methods: Using *Medline*, a systematic review was performed including articles published between January 2000 and September 2016. English language original articles, reviews and editorials were selected based on their clinical relevance.
Results: MWA has several theoretical advantages over radiofrequency ablation in consistently providing higher intratumoral temperatures. MWA is less dependent of electrical conductivities of tissues and the delivered energy is less limited by desiccation of heated tissues. While there are insufficient data, especially because of a lack of studies with mid- to long-term follow-up, to determine the oncologic effectiveness of MWA, this technique appears safe and effective for the ablation of T1 renal tumors. There is evidence for using mid-level settings based on experimental and clinical data. Power set at 50—65 W for 5—15 min appears adequate in kidney but close clinical and imaging follow-up have to be performed.
Conclusion: Renal MWA offers theoretical advantages by comparison with other available techniques to treat renal tumors. However, MWA suffers of less cumulative data compared to radiofrequency ablation or cryoablation. Moreover, microwaves still require further studies to identify the optimal tumor characteristics and device settings leading to predictable ablation.

* Corresponding author.
E-mail address: cornelisfrancois@gmail.com (F.H. Cornelis).

http://dx.doi.org/10.1016/j.diii.2016.12.002
2211-5684/

The early detection of small renal tumors, often in a non-metastatic stage, has considerably modified the management of renal cell carcinomas (RCC) [1—3]. The development of nephron-sparing techniques and ablative therapies are now the standard option for the curative treatment of T1 RCC (< 7 cm) [4]. For patients with small renal cancers who are not amenable to surgery, because of advanced physiological age, comorbidities, or already precarious renal function, the percutaneous approach using thermal ablation is gradually predominating [5]. As conventional ablative techniques such as radiofrequency ablation (RFA) or cryoablation may present limitations in terms of efficacy for tumor greater than 3—4 cm [6,7], new technologies such as microwave ablations (MWA) appear particularly appealing in this context [8,9].

MWA has several theoretical advantages over RFA because it consistently provides higher intratumoral temperatures, is less dependent on electrical conductivities of tissue and because the energy delivery is less limited by the exponential rising electrical impedances of heated tissue [10]. However, MWA suffers of less cumulative data in terms of results by comparison with RFA or cryoablation. Evidence for long-term oncologic efficacy is still lacking.

The purpose of this narrative review was to identify the specific technical considerations to adequately perform MWA of renal tumors and analyze the currently available clinical results.

Evidence acquisition

A systematic Medline/PubMed© literature search was performed with different combinations of terms as ''MWA,'' ''microwave,'' ''kidney,'' ''renal cell carcinoma,'' ''renal tumor.'' Time period included articles published between January 2000 and September 2016. Original articles, reviews and editorials were selected based on their clinical relevance. Cited references from selected articles were analyzed to find and include significant papers previously excluded from our search, including articles published before 2000.

Microwave technology

Microwaves are electromagnetic radiations with wavelengths ranging from one meter to one millimeter corresponding to frequencies between 300-MHz (100 cm) and 300-GHz (0.1 cm). Differently to RFA, which uses ion flow to produce tissue-heating effects, the oscillation of polar molecules producing frictional heating such as water is obtained by microwave exposure, ultimately generating tissue necrosis within solid tumors. At these frequencies, directional changes of water molecules occur 2—5 billion times per second [11]. Microwaves propagate through many types of tissue, even those with low electrical conductivity, high impedance, or low thermal conductivity [12]. In particular, microwaves can penetrate through the charred or desiccated tissues, which tend to build up around all hyperthermic ablation applicators.

Relative permittivity and effective conductivity are the two most important properties to consider for MWA [13]. Permittivity is a material property that affects the Coulomb force between two point charges in the material. The relative permittivity of a material is its (absolute) permittivity expressed as a ratio relative to the permittivity of vacuum and may be considered as the factor by which the electromagnetic field between the charges is decreased relative to vacuum. It may correspond to how well a material will accept an electric field. Relative permittivity determines the wavelength of an applied field at a given frequency, which impacts how well energy will propagate through the tissue and how the antenna is designed [13]. Higher degrees of permittivity lead to shorter wavelengths. Because permittivity is greater in tumoral tissues than in normal tissues, a better diffusion of microwaves is obtained in tumors [14]. It means that marked differences in permittivity between tumors and surrounding tissue may allow better treatment with MWA.

Effective conductivity corresponds to how well the tissue will absorb microwave energy. High water content increases conductivity but absorbs microwaves [13]. Low water content decreases conductivity while increasing the microwave propagation. In the kidney, the high electrical conductivity of kidney allows faster microwave energy absorption but reduces field penetration. However, heating may increase progressively the propagation of microwaves by producing desiccation of tissue and then reduction of conductivity [13].

However, only few data on temperature-dependent dielectric properties of kidney are available in the frequency range of MWA and for various conditions [15]. Fu et al. studied frequency-dependent dielectric properties of various tissues including normal kidney for a range of temperature and frequency (36—60 °C, 42—468 MHz) [16]. The dielectric constant and the conductivity obtained at the same temperature and frequency ranges were 37.3—169.26 and 0.8061—1.3625 S/m. At 2.45 GHz and 37 °C (1.5 cm wavelength), relative permittivity was estimated at 52.8, effective conductivity at 2.43 S/m [13]. Relative permittivity and conductivity measurements made at 915 MHz and 2.45 GHz during thermal ablation tended to drop quickly in all cases when temperatures reached 100 °C and continued to drop as temperature was maintained and the tissue became more dehydrated [17]. Further studies including evaluation of tumoral tissue are mandatory and may help to better establish the most adequate settings of MWA.

Thermal profile of MWA

Compared to RFA, MWA creates larger ablation zones than does a similarly sized RF applicator for similar application time ex-vivo or in preclinical animal model [10]. Temperatures of 160—180 °C are often observed with MWA and temperature increasing is faster than that observed with RFA [10,13,18]. The energy deposition is therefore higher with MWA, less susceptible to heat-sink effect and thermal diffusion. However, thermal diffusion remains depending of tissue characteristics, which may change substantially during heating [13].

Heat transfer in tissue can be modeled using the so-called bioheat transfer equation [19]. The cumulative equivalent minutes at 43 °C (CEM43) is the accepted metric for thermal dose assessment that correlates well with thermal damage in a variety of tissues [20]. While this reference temperature of 43 °C has been arbitrarily chosen to convert all thermal exposures to ''equivalent-minutes'' at this temperature, the CEM43 model is a simple concept that translates all different temperature—time histories to a single number representing a ''thermal isoeffect dose'' [21]. He et al. heat-treated pig kidney at CEM43 between 70 and 7.2×10^4 min using microwaves [22]. On days 2 and 7, consistent tissue damage in the heated region ranged from thermal fixation to coagulative necrosis, and was observed at all doses with histology. However, in the kidney, CEM43 below 20 min causes only acute minor thermal damage [23]. While correlations with MW settings such as power and time and CEM43 have to be performed, these results suggest that adequate renal MWA leads to increase time and/or power in order to reach CEM43 > 70 min and to observe consistent tissue damage.

Authors have recently proposed new quantitative measures, such as ''ablation work'' and ''ablation resistance score'' in treated lung tumors to better analyze thermal ablation zones and to improve treatments in this complex and heterogeneous patient population and tissue environment [24,25]. By measuring the total amount of work as a summation of applicator power and time product over different phases of the ablation, the ''ablation work'' may help to standardize the ablation zone calculation and to improve the understanding of the effects of tissue type, tissue perfusion, adjacent heat sinks, and dielectrical effects and how all of these affect the specific absorption rate of microwave energy during thermal ablation [25]. In further studies, this metric has to be tested in kidneys and may be correlated with CEM43.

Impact of water content of renal tissue

With the evolution of the systems and the use of ceramic antenna, MW efficiency remains more and less similar whatever the temperature for a normal use. However, many factors may theoretically affect the electrical, thermal and mechanical properties of tissue. The most important thing to consider for MWA is the water content of tissue. Electrical properties are dramatically changed when a tissue is heated and temperatures reach 100 °C or above [13]. Water boils and escapes as gas, leading to tissue desiccation. While RF current cannot generally pass through tissues heated above 100 °C because water needed for ion flow is boiled off increasing therefore the impedance, microwaves are usually not affected (Fig. 1) [26]. Microwaves pass through the tissue or gas and may produce heating at any temperature or water content [27]. It explains therefore the reason for improved performance with the use of microwave energy: power is continuously deliver over a target volume during all the treatment sessions [13]. However, thermal injuries of cells occur at temperatures above 50 °C, which may affect the electrical properties of the tissue [26,28].

To summarize, the high water content of the kidney increases initially the heat generation rate while reducing the electromagnetic field penetration. However, the

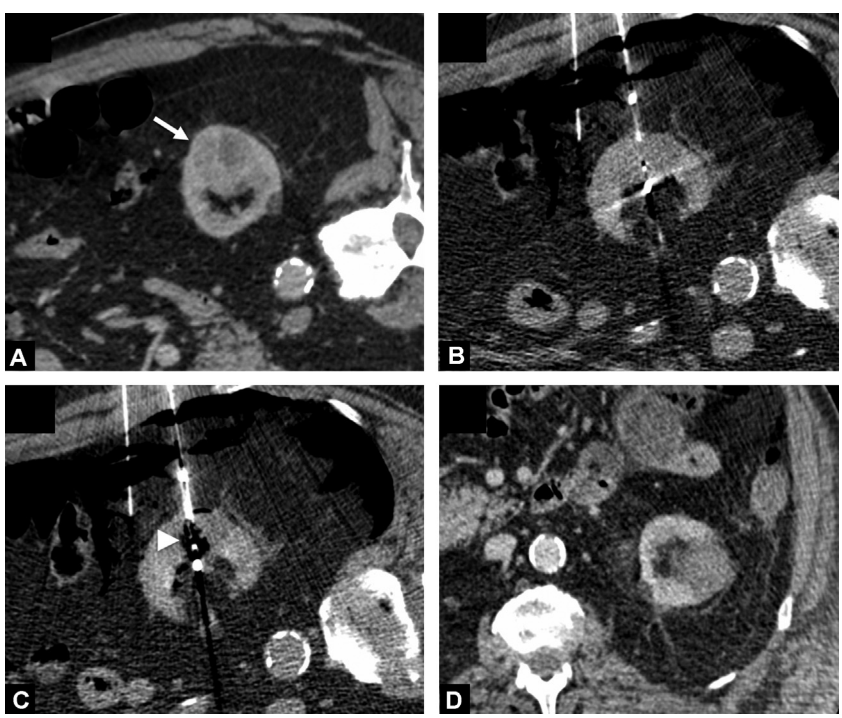

Figure 1. Seventy-nine-year-old man with clear cell carcinoma of the left kidney. A. CT image in the transverse plane obtained after intravenous administration of iodinated contrast material reveals a solid, 35-mm large, clear cell renal carcinoma (arrow) of the left kidney with heterogeneous enhancement. B. A single microwave antenna was inserted into the tumor under CT guidance and general anesthesia. The settings for this ablation were power 75 W and time 11 min. A carbodissection of the perirenal space was performed. C. Gas is observed within the tumor on CT monitoring performed every 2 minutes. D. Follow-up CT scan 3 months after microwave ablation shows the ablation zone. No recurrences were observed during an 18-month follow-up.

microwave propagation changes during ablation since the permittivity and conductivity tend to decrease as tissue becomes dehydrated or injured [17]. This finding suggests that propagation of MW and then the ability of MW to heat a tissue may be therefore improved late in the boundaries of the ablation zone if time of application of MW energy is sufficiently long.

Other considerations

As the kidney is a relatively highly perfused organ (perfusion rate: 3—4 L/min kg), perfusion may affect the ablation volume by sinking heat away from the ablation zone periphery [29]. This is particularly true for tumor close to the renal sinus, next to large vessels or collecting system [30]. As this thermal convection corresponds to the dissipation of heat by a fluid across heated tissues, it may be linked either to the microcirculation or to the macrocirculation. For the microcirculation, the term of ''heat sink effect'' is used. It explains the difficulty to heat tumors that are contiguous to vessels measuring more than 2 to 3 mm. Limited in liver, this effect has not been clearly studied in kidneys but should be higher [31,32]. Although vendor charts describe MWA zones to be ellipsoid, actual ablation zones observed in vivo are often not ellipsoids and may be related to this heat-sink effects as well as tumor (or tissue) inhomogeneity. Therefore, while the fast heating of microwaves may more and less overcome the negative effects of perfusion, it remains still a challenge to predict the limits of ablation (Fig. 2). On the boundaries of MWA, a steady state is obtained: the rate of heat lost to perfusion and to a lesser extent to diffusion is greater than the rate of heat generated at ablation zone periphery [29]. A thermal equilibrium is then obtained, which depends on the distance from the electrode, the type and quantity of energy delivered, and the length of treatment and type of tissue as well as its vascularization [8]. Further evaluations have to be performed in order to identify this thermal equilibrium in the kidneys and to compare these findings with the thermal injuries truly obtained after MWA. To overcome this uncertainty and as proposed for RFA, obtaining larger zones of active heating increasing thermal gradient may limit the effect of perfusion [33]. For this purpose, longer active zone or several probes may be used simultaneously [34]. Stopping the blood flow using balloon catheter may also be an option [35].

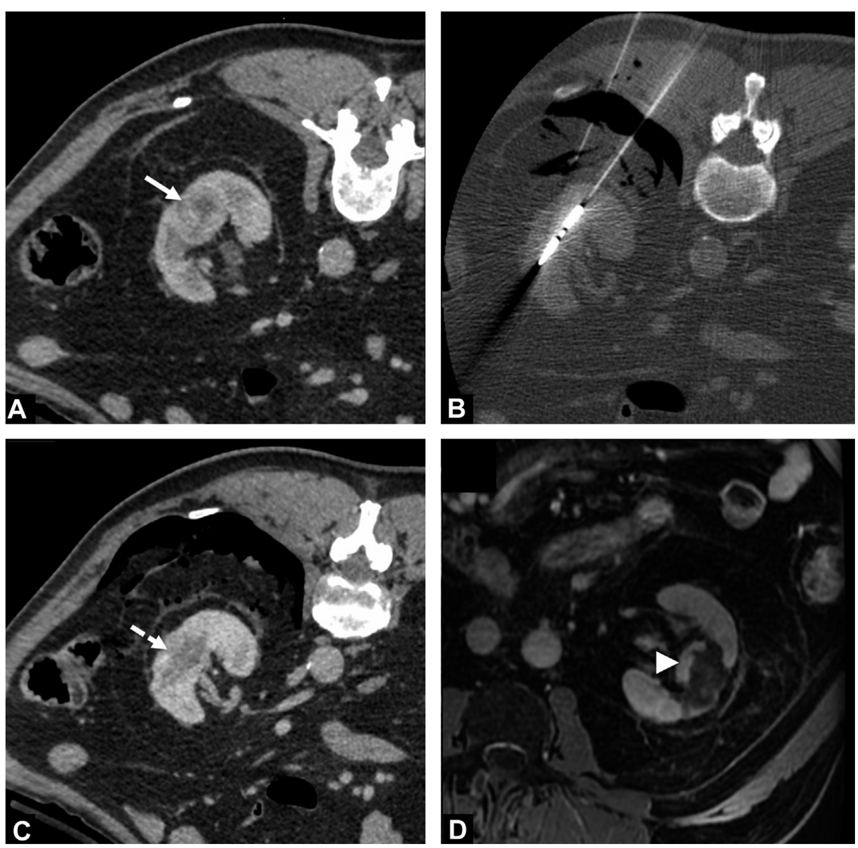

Figure 2. Seventy-eight-year-old man with clear cell carcinoma of the left kidney. A. CT image in the transverse plane obtained after intravenous administration of iodinated contrast material reveals a solid, 37-mm, clear cell renal carcinoma (arrow) of the left kidney with heterogeneous enhancement. B. Two microwave antennas were inserted into the tumor under CT guidance and general anesthesia. The settings for this ablation were power: 90 W (45 W each antenna) and time: 10 min. A carbodissection of the perirenal space was performed. C. After microwave ablation, the shape of the ablation remained relatively linear (dashed arrow). Heterogeneous enhancement is observed at the boundaries of the ablation zone so that early control was planned to detect early recurrence or incomplete treatment. D. Dynamic fat-attenuated T1-weighted MR image (3.9/1.8/10°) obtained after intravenous administration of a gadolinium chelate one month later shows residual tumor tissue close to the renal pelvis (arrowhead). Additional radiofrequency ablation was performed to treat residual tumor.

Available techniques for MWA

Several microwave systems are commercially available worldwide [12,36]. Power is generated using either magnetron or solid-state sources. The systems use either a 915-MHz or a 2450-MHz generator as allowed by the Federal Communications Commission. These frequencies are much higher than radiofrequency and allow microwave antennas to emit in the body without ground pads. While 915 MHz frequency suggests deeper field penetration, no comparisons have been performed to date with the 2.45-GHz frequency for large-volume ablation in the kidney.

Microwave power is carried from the generator to the antenna through coaxial cables, often rigid, due to power handling — the ability of a cable to safely transfer power without overheating or failure — and the frequency of the applied microwave power [37]. The MW antennas are straight applicators with active tips ranging in lengths from 0.6 to 4.0 cm and are available in several diameters or lengths. Antenna properties include both the radiation pattern and reflection coefficient, or return loss. This later has to be as lower as possible to maximize energy transfer from the antenna into the tissue. Therefore, MW antenna design is a balance of power efficiency, tissue heating pattern, and antenna diameter with design tradeoffs necessary to produce a specific desired result [12]. Energy reflected from the antenna reduces tissue heating, while increasing unwanted heating of the antenna shaft and risk of skin burn. Several antenna designs are available to reduce return loss and focused energy radiation [37]. Then, using a centrifugal method, energy dissipates towards the periphery from a single applicator inserted into the center of the targeted tumor [9]. In some cases, an overlapping ablation strategy may be required in order to treat the whole lesion with sufficient margins. This may be achieved by multiple reinsertion of a single device or by using several applicators. Multiple antennas can be operated simultaneously in close proximity without switching [34]. As antennas may be positioned and phased to exploit overlap of the electromagnetic field, ablation strategy involving centripetal convergence of energy from the periphery towards the center of the tumor may be performed [9,12].

During the last few years, several evolutions have been observed, as some of the limitations of the earlier generation devices had been unpredictable size and shape of the ablation zones across the different tissue types. Heating precision was limited by the 2—4 cm wavelength penetration of microwave energy in tissue and rapid heating associated with high temperatures were sometimes an issue safety when applied over a large volume [37]. First-generation systems lacked active antenna cooling but operated at low power. Burns were observed as a rapid heating along the entire length of the antenna was observed. Optimization of generator power and antenna cooling capabilities have been proposed [38]. Second-generation systems had active antenna cooling but still operated with a low-power generator. Unpredictable ablation volume was therefore obtained limiting the clinical efficacy while increasing the risks of complications locally if inadequate settings were used. Third-generation systems have now both active antenna cooling and high-power generators. The antennas are internally cooled with either room-temperature fluid or carbon dioxide. It reduces conductive heating along the needle path and prevent possible skin damage [39]. Moreover, several technologies have been proposed in order to obtain more precise and predictable ablation volume by adjusting the energy delivery. Field and wavelength control, in addition of thermal control, maintain a precise, predictable and spherical ablation zone throughout the procedures [40,41]. The antennas have now a geometry that focuses energy at the tip of the device generating a precise spherical electromagnetic field (so-called field control). The synchronous wave alignment may allow non-parallel placement and avoid skipping when using multiple antennas. This system entails a temporal synergy between the multiple antennae inducing a single large area of the ablation areas produced from every single device.

Results of experimental studies

Experimental studies performed in porcine kidneys have reported the feasibility of MWA as well as the pathological characteristics according to several experimental settings. Sommer et al. studied two methods of performing MWA: power control versus temperature control [42]. Microwave ablations performed with temperature control showed fewer system failures and were finished faster. Both ablation modes demonstrated no significant differences with respect to ablation geometry. Compared to RFA, MWA created larger ablation zones in normal porcine kidneys than RFA with similarly sized applicators [43]. Single-antenna microwave ablation zones were significantly larger than single-electrode RF zones ($P = 0.03$). No significant differences were detected between single-antenna microwave and multiple-electrode RF.

Renal tissues after MWA are thoroughly necrotic [44]. Coagulative necrosis is observed in coagulation area, though there are residual profile of glomerulus, renal tubular and vessels, they had lost activity. Most of the tissues in transition zone are normal, however, some cells were swelling because of thermal damage. Hope et al. tested in vivo several independent variables such as power (20, 30, 40, 45, 50, 60 W) and time (2, 4, 6, 8, 10, 15, 20 min) [45]. While the outcome variable, ablation diameter, was affected significantly by time, power, and time/power interaction ($P < 0.0001$), ablation sizes at 45, 50, and 60 W were not significantly different at each time point. Therefore, authors recommended use at 45 W for 10 min. Bartoletti et al. reported similar relation to both power and time of exposure with size of ablation [46]. Again, the 50 W power particularly induces necrotic renal lesions as a function of the time of exposure. These conclusions appear concordant with the technical considerations for renal ablation with MW: the ablation volume is related to the propagation of energy into the kidney, which may be increased at the periphery if heating is sufficiently long. However, close to the collecting system, the ablated zones at 45 W for 3, 5, and 10 minutes interval appeared inconsistent for Moore et al. [47]. The antenna tract was charred, the collecting system was damaged, and there was asymmetry of the zones of ablation. Histological analysis revealed coagulative necrosis in the area of the ablation with sloughed and denuded urothelium. The authors concluded that MWA of the kidney yields inconsistent geometrical lesions when applied near the renal collecting system. For the authors, the increased water content in the collecting system resulting in damage to it may preferentially absorb microwave energy. These later results have to be considered when performing a MWA in tumor centrally located and settings have probably to be adjusted.

Although not evaluate in kidneys, Ahmed et al. showed that hepatic MWA promoted periablational inflammation and increased distant tumor growth similar to RFA in an animal tumor model [48,49]. However, the authors suggested that higher-power, faster heating protocols may potentially mitigate such undesired effects [49]. These considerations have to be explored in renal tissue in further studies.

Clinical results

Procedures

After an adequate hydro- or carbodissection, most of the studies reported that duration of the ablation cycle depends upon the time necessary for gas to cover the index tumor and to observe circumferential 5 mm margin surrounding the tumor [5,50]. Vaporization is most prevalent in the central part of the ablation zone where highest temperatures are present but gas diffuses along the temperature gradient [51]. After MWA, ablation zones are significantly smaller than the pretreatment tissue dimensions mostly due to water dehydration but also collagen shrinkage (Fig. 3) [52]. The total ablation volume may decrease up to 45% with a greater tissue contraction near the center but lower at the edge of the ablation zone [52]. Contraction rate peaks early following an exponential curve, with the greatest rates occurring in the first 60 s, and decays over time. A decrease in density of the tumor and surrounding tissue such as fat may be also expected due to the desiccation (Fig. 3). As a routine, the MW generator is initially powered at 50—65 W for a single antenna for a prescribed time of 5—10 min [50,53,54], which may be secondarily adjusted. Initial settings depend on tumor location, tumor size and the expected margins. When phased constructively, heating increases proportional to the square of the number of antennas, allowing more efficient heating and generation of higher temperatures when compared to a single antenna [12]. Therefore, for a MWA procedure with several antennas, the power of each single antenna has to be decreased in order to obtain an overall power concordant with the tumor volume.

An intermittent follow-up is performed either using computed tomography (CT) or ultrasound every 2—3 min [50,53,54], If the tumor and margins are covered prior to the prescribed time, the ablation cycle is terminated and the antenna removed. However, if the tumor and margins are not adequately covered with the initial ablation cycle, additional time is often prescribed or the antennas repositioned and powered again. Some researchers proposed alternatively to perform a short boost using higher settings (100—120 W) for a short time (less than 5 min) after a first heating. Again, an intermittent follow-up is performed either by CT or ultrasound to identify the margins.

Safety and efficacy

The clinical results of MWA are summarized in Table 1. The feasibility of MWA on human renal tissue was initially described in 2007 by Clark et al. [55]. This study

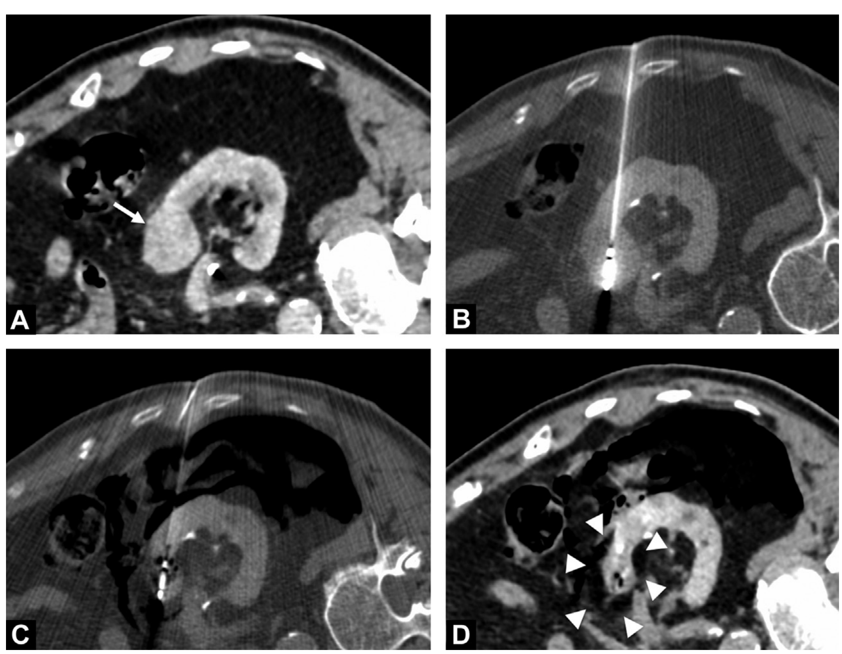

Figure 3. Eight-four-year-old man with clear cell carcinoma of the left kidney. A. CT image in the transverse plane obtained after intravenous administration of iodinated contrast material reveals a solid, 31-mm, clear cell renal carcinoma (arrow) of the left kidney with heterogeneous enhancement. B. One single microwave antenna was inserted into the tumor under CT guidance and general anesthesia. The settings for this ablation were power: 75 W and time: 12 min. A carbodissection of the perirenal space was performed to remove the small bowel from the ablation zone. C. Gas is observed within the tumor on CT monitoring performed every 2 minutes. D. Final control CT image shows tumor shrinkage. Fat surrounding the tumor (arrowhead) is markedly hypoattenuating due to fatty tissue desiccation. No recurrences were observed on subsequent imaging follow-up.

Table 1 Clinical results of microwave ablation of renal tumors.

Authors [ref. number]	Year	Patients/ Tumor	Mean tumor size[a] (mm) [range]	Technique used	Mean ablation volume (cm^3)	Follow-up (months)[a] [range]	Complications according Clavien-Dindo classification	Outcomes
Clark et al. [55]	2007	10/10	[39—110]	Laparoscopic, 915 MHz, VivaWave (Vivant Medical) 1—3 probes 60 W/10 min	Single probe: 15 cm^3 (4—27.7) Three-probe array: 56 cm^3, (31.5—78.8)	—	—	Tumors were surgically removed
Carrafiello et al. [57]	2010	12/12	20 [17—29]	Percunatenous, 915 MHz, VivaWave (Vivant Medical) 1—3 probes 45 W/10 min	17.2 cm^3 (10.2—25.1)	Mean: 6 [3—14]	1 grade I (pain)	Technical success: 100% Clinical effectiveness: 100%
Castle et al. [58]	2011	10/10	36.5 [20—55]	Laparoscopic or percutaneous, 915 MHz, Valleylab Evident MWA system (Covidien) 1—3 probes 45 W, 10—35 min, percu	—	Mean: 17.9 [14—24]	6 grade I (pleuritic chest pain, skin burn, fever of unknown origin, hematuria, genitofemoral neuralgia, and flank pain) 3 grade III (urinoma, necrosis of ureteropelvic junction, foreign body)	38% recurrences identified at 3, 4, and 21 months
Guan et al. [60]	2012	48/48	31 [12—39]	Laparoscopic, 2450 MHz, KY-2000 MWA system (Kangyou Medical Instrument) 1 probe 50 W/8 min secondarly adaptated on temperature	—	Mean: 32 [24—54]	4 grade I (pain) 1 grade II (hematuria) 1 grade III (urine leak and abcess)	2 incomplete ablations (4.2%) 2 recurrences (4.2%) RFS: 91.3% (74.7—97.2), DSS: 100%
Yu et al. [54]	2012	46/49	30 [6—77]	Percutaneous, 2450 MHz, KY-2000 MWA system (Kangyou Medical Instrument) 1 probe 50.2 (±2.9) W/8.4 (±4.1, 2.5—25.5) min secondarly adaptated on temperature	—	Median: 20.1 [4—58.9]	1 grade II (hematoma)	Metastasis FS: 100% 1-, 2-, and 3-year LTP: 4.6%, 7.7%, and 7.7% 1-, 2-, and 3-year DFS: 95.4%, 92.3%, and 92.3% DSS: 100%

Table 1 (*Continued*)

Authors [ref. number]	Year	Patients/ Tumor	Mean tumor size[a] (mm) [range]	Technique used	Mean ablation volume (cm^3)	Follow-up (months)[a] [range]	Complications according Clavien-Dindo classification	Outcomes
Yu et al. [59]	2014	65/69	27 [6–40]	Percutaneous, 2450 MHz, KY-2000 MWA system (Kangyou Medical Instrument) 1 probe 50 W/10 min secondarly adaptated on temperature	–	Median: 20.3 [4.3–75.2]	2 grade III (hepatic encephalopathy, urinary fistula)	Technical success: 100%, 1-, 3-, and 5-year metastasis-free survival: 97.9%, 87.4%, 65.5%, 1-, 3-, and 5-year specific survival rates: 97.1%, 97.1%, 97.1%
Moreland et al. [53]	2014	53/55	26 [8–40]	Percutaneous, Certus 140 (NeuWave Medical) 1–3 probes, 65 W/5 min (5–7)	Tumor volume decreased by a median of 52% (IQR 36%–67%) on immediate postablation CT	Median: 8 (IQR: 5–18.25)	5 grade I (urine retention, fluid overload, atrial fibrillation) 1 grade II (hemorrhage)	No recurrences
Lin et al. [61]	2014	14/16	31.5 [10–84]	Percutaneous, 2450 MHz, KY-2000 MWA system (Kangyou Medical Instrument) 1 probe 50 W/10 min secondarly adaptated on temperature	–	Median 9.5 [1–56.4]	5 grade I-II (pain, hamatoma, hematuria)	93.8% complete ablation, cancer-specific survival rate: 85.7%
Wells et al. [50]	2016	29/30	Median: 31 (IQR: 23–38)	Percutaneous, Certus 140 (NeuWave Medical) 1–3 probes, 65 W/5 min (IQR 4–6.25)	–	Median: 12 [IQR: 6–18]	1 grade I (urine leak) 2 grade II (pneumonia, cystitis)	Technical success: 97% No recurrences LTP: 0% Cancer specific survival: 97%

RFS: recurrence free survival rate; DFS: disease specific survival rate; DSS: disease specific survival; LTP: local tumor progression; 95% CI: 95% confidence interval; IQR: interquartile range.

[a] Numbers in brackets are ranges unless specified.

demonstrated the capability of microwave to destroy renal lesions up to 5.7 cm. Soon after, Liang et al. treated 12 patients with renal cell carcinomas (1.3—3.8 cm in diameter) with microwave and found complete ablation in a single session with no residual or recurrent tumor at a median follow-up of 11 months [56]. While Carrafiello et al. reported a 100% efficacy after ablation of 12 exophytic renal tumors less than 3 cm for a mean follow-up of 6 months (3—14), Castle et al. reported 38% recurrence rate at 18 months follow-up (mean tumor size: 3.65 cm; range: 2—5.5 cm) [57,58]. In addition, 20% of patients experienced a grade 3 complication. These results may be related to the first-generation material used. Recently, in a retrospective review of 29 consecutive patients with a total of 30 RCC (23 T1a; 7 T1b), a technical success was achieved for 22 T1a (96%) and 7 T1b (100%) tumors using a third generation system [50]. No local tumor progressions as well as no severe complications were observed during a median imaging follow-up of 12.0 months (interquartile range [IQR]: 6—18 months). Only three (10%) Clavien-Dindo grade I—II adverse effects were detected. Similarly, Yu et al. retrospectively reviewed intermediate-term (median: 20.1 months) clinical outcomes after ultrasound-guided MWA in 46 patients with 49 RCC nodules (diameter: 0.6—7.7 cm) [54]. Technical effectiveness was achieved in 48 of 49 (98.0%) tumors, and the metastasis-free rate was 100% (46 of 46). The 1-, 2-, and 3-year local tumor progression rates were 4.6%, 7.7%, and 7.7%, respectively while the 1-, 2-, and 3-year disease-free survival rates were 95.4%, 92.3%, and 92.3%, respectively. No major complications occurred. The authors showed that tumor number ($P = 0.046$), tumor growth patterns ($P = 0.003$), and ablation time ($P = 0.04$) were independent unfavorable prognostic factors in a multivariate analysis. After comparison with open radical nephrectomy (ORN), the same team showed that MWA had similar results [59]. A total of 163 patients (127 men and 36 women) with small RCC (≤ 4 cm) were included: 65 patients underwent MWA and 98 patients underwent ORN. RCC-related survival was similar to that of ORN ($P = 0.78$) and estimated cancer-related survival, estimated 5-year rates were 97.1% after MWA and 97.8% after ORN. There was one local tumor recurrence 32 months after MWA and none after ORN. Major complication rates were similar ($P = 0.81$) between the two techniques (MWA, 2.5% vs. ORN, 3.1%). The MWA group had less surgical time ($P < 0.001$), estimated blood loss ($P < 0.001$), and postoperative hospitalization ($P < 0.001$). A prospective randomized comparison of intermediate-term outcomes of patients with small renal tumors who were treated with partial nephrectomy (PN) or microwave ablation was performed by Guan et al. [60]. Among the patients treated, 54 had either open ($n = 19$) or laparoscopic ($n = 35$) PN and 48 had laparoscopic ($n = 28$) or open ($n = 20$) microwave ablation. Estimated blood loss, complication rates, and decline of postoperative renal function were significantly less in the microwave ablation group ($P = 0.0002$, $P = 0.0187$, and $P = 0.0092$, respectively). The overall local recurrence-free survival at 3 years were 91.3% for microwave ablation and 96.0% for PN ($P = 0.5414$). Moreland et al. reported the outcomes after 53 consecutive MWA in 53 patients with biopsy-proven RCC ≤ 4 cm (55 tumors) [53]. The mean tumor diameter was 2.6 cm (range: 0.8—4.0 cm). During the follow-up (median: 8 months; IQR: 5—18.25), no patients demonstrate evidence of local recurrence or metastasis. Six low-grade complications (11.3%) were recorded: five Clavien-Dindo grade I (urine retention, fluid overload, and atrial fibrillation) and one grade II (hemorrhage requiring transfusion). The postprocedure estimated glomerular filtration rate was not significantly changed from preprocedure levels (median: −1.1%, $P = 0.10$). Interestingly, Lin et al. also demonstrated the preservation of renal function in 14 solitary renal tumors treated by MWA [61].

Conclusion

While there are insufficient data and studies with mid- to long-term follow-up are currently lacking to determine its oncologic effectiveness, MWA appears safe and effective when ablating T1 RCC. There is evidence to use mid-level settings. Based on experimental and clinical data, power set at 50—65 W for 5 to 15 min appears adequate in kidney but attentive clinical and imaging follow-up have to be performed. Clinical studies are now mandatory on a larger scale and using different systems before drawing definitive conclusions [62].

Funding

No funding source.

Disclosure of interest

The authors declare that they have no competing interest.

References

[1] Bosniak MA, Birnbaum BA, Krinsky GA, Waisman J. Small renal parenchymal neoplasms: further observations on growth. Radiology 1995;197:589—97.

[2] Homma Y, Kawabe K, Kitamura T, Nishimura Y, Shinohara M, Kondo Y, et al. Increased incidental detection and reduced mortality in renal cancer — recent retrospective analysis at eight institutions. Int J Urol 1995;2:77—80.

[3] Iguchi T, Hiraki T, Tomita K, Gobara H, Fujiwara H, Sakurai J, et al. Simultaneous biopsy and radiofrequency ablation of T1a renal cell carcinoma. Diagn Interv Imaging 2016, http://dx.doi.org/10.1016/j.diii.2016.05.001.

[4] Campbell SC, Novick AC, Belldegrun A, Blute ML, Chow GK, Derweesh IH, et al. Guideline for management of the clinical T1 renal mass. J Urol 2009;182:1271—9.

[5] Cornelis F, Balageas P, Le Bras Y, Rigou G, Boutault JR, Bouzgarrou M, et al. Radiologically-guided thermal ablation of renal tumours. Diagn Interv Imaging 2012;93:246—61.

[6] Balageas P, Cornelis F, Le Bras Y, Hubrecht R, Bernhard JC, Ferriere JM, et al. Ten-year experience of percutaneous image-guided radiofrequency ablation of malignant renal tumours in high-risk patients. Eur Radiol 2013;23:1925—32.

[7] Psutka SP, Feldman AS, McDougal WS, McGovern FJ, Mueller P, Gervais DA. Long-term oncologic outcomes after radiofrequency ablation for T1 renal cell carcinoma. Eur Urol 2013;63:486—92.

[8] de Baere T, Deschamps F. New tumor ablation techniques for cancer treatment (microwave, electroporation). Diagn Interv Imaging 2014;95:677—82.
[9] Seror O. Ablative therapies: advantages and disadvantages of radiofrequency, cryotherapy, microwave and electroporation methods, or how to choose the right method for an individual patient? Diagn Interv Imaging 2015;96:617—24.
[10] Yu J, Liang P, Yu X, Liu F, Chen L, Wang Y. A comparison of microwave ablation and bipolar radiofrequency ablation both with an internally cooled probe: results in ex vivo and in vivo porcine livers. Eur J Radiol 2011;79:124—30.
[11] Simon CJ, Dupuy DE, Mayo-Smith WW. Microwave ablation: principles and applications. Radiographics 2005;25:69—83.
[12] Lubner MG, Brace CL, Hinshaw JL, Lee Jr FT. Microwave tumor ablation: mechanism of action, clinical results, and devices. J Vasc Interv Radiol 2010;21:S192—203.
[13] Brace CL. Radiofrequency and microwave ablation of the liver, lung, kidney, and bone: what are the differences? Curr Probl Diagn Radiol 2009;38:135—43.
[14] Stuchly MA, Athey TW, Stuchly SS, Samaras GM, Taylor G. Dielectric properties of animal tissues in vivo at frequencies 10 MHz — 1 GHz. Bioelectromagnetics 1981;2:93—103.
[15] Rossmanna C, Haemmerich D. Review of temperature dependence of thermal properties, dielectric properties, and perfusion of biological tissues at hyperthermic and ablation temperatures. Crit Rev Biomed Eng 2014;42:467—92.
[16] Fu F, Xin SX, Chen W. Temperature- and frequency-dependent dielectric properties of biological tissues within the temperature and frequency ranges typically used for magnetic resonance imaging-guided focused ultrasound surgery. Int J Hyperth 2014;30:56—65.
[17] Brace CL. Temperature-dependent dielectric properties of liver tissue measured during thermal ablation: toward an improved numerical model. Conf Proc IEEE Eng Med Biol Soc 2008;2008:230—3.
[18] Brace CL, Hinshaw JL, Laeseke PF, Sampson LA, Lee Jr FT. Pulmonary thermal ablation: comparison of radiofrequency and microwave devices by using gross pathologic and CT findings in a swine model. Radiology 2009;251:705—11.
[19] Pennes HH. Analysis of tissue and arterial blood temperatures in the resting human forearm. J Appl Physiol 1948;1:93—122.
[20] Dewhirst MW, Viglianti BL, Lora-Michiels M, Hanson M, Hoopes PJ. Basic principles of thermal dosimetry and thermal thresholds for tissue damage from hyperthermia. Int J Hyperth 2003;19:267—94.
[21] Sapareto SA, Dewey WC. Thermal dose determination in cancer therapy. Int J Radiat Oncol Biol Phys 1984;10:787—800.
[22] He X, McGee S, Coad JE, Schmidlin F, Iaizzo PA, Swanlund DJ, et al. Investigation of the thermal and tissue injury behaviour in microwave thermal therapy using a porcine kidney model. Int J Hyperth 2004;20:567—93.
[23] Yarmolenko PS, Moon EJ, Landon C, Manzoor A, Hochman DW, Viglianti BL, et al. Thresholds for thermal damage to normal tissues: an update. Int J Hyperth 2011;27:320—43.
[24] Al-Hakim RA, Abtin FG, Genshaft SJ, Kutay E, Suh RD. Defining new metrics in microwave ablation of pulmonary tumors: ablation work and ablation resistance score. J Vasc Interv Radiol 2016;27:1380—6.
[25] Dupuy DE, Keshava Murthy KN, Patel L. Can we predict lung ablation success by power and location alone? J Vasc Interv Radiol 2016;27:1387—8.
[26] Vogl TJ, Naguib NN, Lehnert T, Nour-Eldin NE. Radiofrequency, microwave and laser ablation of pulmonary neoplasms: clinical studies and technical considerations — review article. Eur J Radiol 2011;77:346—57.
[27] Sidoff L, Dupuy DE. Clinical experiences with microwave thermal ablation of lung malignancies. Int J Hyperth 2016:1—9.
[28] Goldberg SN, Gazelle GS, Mueller PR. Thermal ablation therapy for focal malignancy: a unified approach to underlying principles, techniques, and diagnostic imaging guidance. AJR Am J Roentgenol 2000;174:323—31.
[29] Cornelis F, Grenier N, Moonen CT, Quesson B. In vivo characterization of tissue thermal properties of the kidney during local hyperthermia induced by MR-guided high-intensity focused ultrasound. NMR Biomed 2011;24:799—806.
[30] Rouviere O, Badet L, Murat FJ, Marechal JM, Colombel M, Martin X, et al. Radiofrequency ablation of renal tumors with an expandable multitined electrode: results, complications, and pilot evaluation of cooled pyeloperfusion for collecting system protection. Cardiovasc Interv Radiol 2008;31:595—603.
[31] Lencioni R, de Baere T, Martin RC, Nutting CW, Narayanan G. Image-guided ablation of malignant liver tumors: recommendations for clinical validation of novel thermal and non-thermal technologies — a western perspective. Liver Cancer 2015;4:208—14.
[32] De Baere T, Tselikas L, Pearson E, Yevitch S, Boige V, Malka D, et al. Interventional oncology for liver and lung metastases from colorectal cancer: the current state of the art. Diagn Interv Imaging 2015;96:647—54.
[33] Takaki H, Soga N, Kanda H, Nakatsuka A, Uraki J, Fujimori M, et al. Radiofrequency ablation versus radical nephrectomy: clinical outcomes for stage T1b renal cell carcinoma. Radiology 2014;270:292—9.
[34] Brace CL, Laeseke PF, Sampson LA, Frey TM, van der Weide DW, Lee Jr FT. Microwave ablation with multiple simultaneously powered small-gauge triaxial antennas: results from an in vivo swine liver model. Radiology 2007;244:151—6.
[35] Yoon SK, Choi JC, Cho JH, Oh JY, Nam KJ, Jung SI, et al. Radiofrequency ablation of renal VX2 tumors with and without renal artery occlusion in a rabbit model: feasibility, therapeutic efficacy, and safety. Cardiovasc Interv Radiol 2009;32:1241—6.
[36] Hoffmann R, Rempp H, Erhard L, Blumenstock G, Pereira PL, Claussen CD, et al. Comparison of four microwave ablation devices: an experimental study in ex vivo bovine liver. Radiology 2013;268:89—97.
[37] Brace CL. Microwave tissue ablation: biophysics, technology, and applications. Crit Rev Biomed Eng 2010;38:65—78.
[38] Higgins LJ, Hong K. Renal ablation techniques: state of the art. AJR Am J Roentgenol 2015;205:735—41.
[39] Dupuy DE. Image-guided thermal ablation of lung malignancies. Radiology 2011;260:633—55.
[40] Alonzo M, Bos A, Bennett S, Ferral H. The emprint ablation system with thermosphere technology: one of the newer next-generation microwave ablation technologies. Semin Intervent Radiol 2015;32:335—8.
[41] Ierardi AM, Mangano A, Floridi C, Dionigi G, Biondi A, Duka E, et al. A new system of microwave ablation at 2450 MHz: preliminary experience. Updat Surg 2015;67:39—45.
[42] Sommer CM, Arnegger F, Koch V, Pap B, Holzschuh M, Bellemann N, et al. Microwave ablation of porcine kidneys in vivo: effect of two different ablation modes (''temperature control'' and ''power control'') on procedural outcome. Cardiovasc Interv Radiol 2012;35:653—60.
[43] Laeseke PF, Lee Jr FT, Sampson LA, van der Weide DW, Brace CL. Microwave ablation versus radiofrequency ablation in the kidney: high-power triaxial antennas create larger ablation zones than similarly sized internally cooled electrodes. J Vasc Interv Radiol 2009;20:1224—9.
[44] Hong B, Chen G, Zhao Y, Du X, Yang Y, Zhang X, et al. Experimental study on ablation zone and characteristics of microwave ablation in porcine kidney in vitro. Zhonghua Yi Xue Za Zhi 2015;95:2644—6.
[45] Hope WW, Schmelzer TM, Newcomb WL, Heath JJ, Lincourt AE, Norton HJ, et al. Guidelines for power and time variables for

microwave ablation in an in vivo porcine kidney. J Surg Res 2009;153:263—7.
[46] Bartoletti R, Cai T, Tosoratti N, Amabile C, Crisci A, Tinacci G, et al. In vivo microwave-induced porcine kidney thermoablation: results and perspectives from pilot study of a new probe? BJU Int 2010;106:1817—21.
[47] Moore C, Salas N, Zaias J, Shields J, Bird V, Leveillee R. Effects of microwave ablation of the kidney. J Endourol 2010;24:439—44.
[48] Ahmed M, Kumar G, Moussa M, Wang Y, Rozenblum N, Galun E, et al. Hepatic radiofrequency ablation-induced stimulation of distant tumor growth is suppressed by c-met inhibition. Radiology 2016;279:103—17.
[49] Velez E, Goldberg SN, Kumar G, Wang Y, Gourevitch S, Sosna J, et al. Hepatic thermal ablation: effect of device and heating parameters on local tissue reactions and distant tumor growth. Radiology 2016;281:782—92.
[50] Wells SA, Wheeler KM, Mithqal A, Patel MS, Brace CL, Schenkman NS. Percutaneous microwave ablation of T1a and T1b renal cell carcinoma: short-term efficacy and complications with emphasis on tumor complexity and single session treatment. Abdom Radiol 2016;41:1203—11.
[51] Yang D, Converse MC, Mahvi DM, Webster JG. Expanding the bioheat equation to include tissue internal water evaporation during heating. IEEE Trans Biomed Eng 2007;54:1382—8.
[52] Liu D, Brace CL. CT imaging during microwave ablation: analysis of spatial and temporal tissue contraction. Med Phys 2014;41:113303.
[53] Moreland AJ, Ziemlewicz TJ, Best SL, Hinshaw JL, Lubner MG, Alexander ML, et al. High-powered microwave ablation of t1a renal cell carcinoma: safety and initial clinical evaluation. J Endourol 2014;28:1046—52.
[54] Yu J, Liang P, Yu XL, Cheng ZG, Han ZY, Mu MJ, et al. US-guided percutaneous microwave ablation of renal cell carcinoma: intermediate-term results. Radiology 2012;263:900—8.
[55] Clark PE, Woodruff RD, Zagoria RJ, Hall MC. Microwave ablation of renal parenchymal tumors before nephrectomy: phase I study. AJR Am J Roentgenol 2007;188:1212—4.
[56] Liang P, Wang Y, Zhang D, Yu X, Gao Y, Ni X. Ultrasound guided percutaneous microwave ablation for small renal cancer: initial experience. J Urol 2008;180:844—8.
[57] Carrafiello G, Mangini M, Fontana F, Recaldini C, Piacentino F, Pellegrino C, et al. Single-antenna microwave ablation under contrast-enhanced ultrasound guidance for treatment of small renal cell carcinoma: preliminary experience. Cardiovasc Interv Radiol 2010;33:367—74.
[58] Castle SM, Salas N, Leveillee RJ. Initial experience using microwave ablation therapy for renal tumor treatment: 18-month follow-up. Urology 2011;77:792—7.
[59] Yu J, Liang P, Yu XL, Cheng ZG, Han ZY, Zhang X, et al. US-guided percutaneous microwave ablation versus open radical nephrectomy for small renal cell carcinoma: intermediate-term results. Radiology 2014;270:880—7.
[60] Guan W, Bai J, Liu J, Wang S, Zhuang Q, Ye Z, et al. Microwave ablation versus partial nephrectomy for small renal tumors: intermediate-term results. J Surg Oncol 2012;106:316—21.
[61] Lin Y, Liang P, Yu XL, Yu J, Cheng ZG, Han ZY, et al. Percutaneous microwave ablation of renal cell carcinoma is safe in patients with a solitary kidney. Urology 2014;83:357—63.
[62] Denys A, de Baere T. The virtuous circle of building evidence in abdominal interventional radiology. Diagn Interv Imaging 2015;96:529—30.