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REVIEW

Adjunctive Thermoprotection During Percutaneous Thermal Ablation Procedures: Review of Current Techniques

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Abstract Although rare, unintended thermal injury to organs surrounding the ablation zone can lead to severe complications. Over the past 15 years, different protective methods have been developed to limit risk of complications, and expand indications to include more challenging lesions in various locations including liver, kidney, lung and bone. The most frequently used techniques include hydrodissection, carbodissection, balloon interposition and probe torqueing. In most cases, tumours can be physically separated from sensitive structures, reducing risk of thermal injury. Endoluminal cooling/warming is an alternative option for complex ablations close to the ureter or major bile ducts. Different techniques may be combined to achieve successful protection in locations with complex anatomy. The purpose of this review is to provide an overview of available protective measures and discuss respective advantages/drawbacks.

Keywords Percutaneous thermal ablation · Protection · Cryoablation · Radiofrequency ablation · Hydrodissection

Introduction

Percutaneous thermal ablation is an effective treatment for benign and malignant tumours in various locations (e.g. lung, liver, kidney, adrenal, bone and soft tissue) [1–5]. Although minimally invasive, the technique carries a risk of thermal injury to sensitive structures in the vicinity of the ablation zone and may result in a range of complications depending on target lesion location, including biliary/diaphragmatic injury (liver), pelvicalyceal/ureteric stricture (kidney), bowel perforation (liver, kidney, adrenal) and nerve deficit

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(bone/soft tissue) [6–8]. Initially, a distance of less than 1 cm between the tumour and vulnerable surrounding organ was considered a contraindication for thermal ablation [9, 10]. Most operators continue to recommend a minimum 1-cm "rule of thumb" safety margin for all tumour type/locations, ablation modalities and adjunctive protection techniques; however, larger (e.g. kidney) or smaller (e.g. spine, liver) distances may be appropriate in selected cases.

Several different thermo-protective techniques have been developed in order to expand indications for thermal ablation while limiting risk of complications. These techniques have continuously evolved with the development of novel ablation modalities [e.g. microwave ablation (MWA) and cryoablation (CA)] and newer treatable anatomic locations [11–14]. The purpose of the present paper is to review the spectrum of available thermo-protective measures, illustrate their principles and discuss respective advantages/drawbacks.

External Displacement

External organ displacement has been described in the literature for complex approaches during percutaneous abdominal biopsies. Manual compression or external compression devices may displace bowel loops away from target lesions, improving lesion accessibility [15, 16]. Tuncali et al. utilised external displacement of bowel loops during MRI-guided cryoablation (CA); with manual compression, the authors achieved between 0.8 and 2.6 cm separation between tumour and bowel, enabling safe ablation without immediate or delayed perforation [17]. The principal drawback is that external/manual pressure has to be maintained during the entire procedure, limiting its use during CT-guided ablation. As a passive protection method, it is compatible with CA (where ice ball margins are well seen), but more limited during heat-based therapies, where ablation zone margins are poorly defined and adequate separation is difficult to verify.

Endoluminal Cooling/Warming

The principle of endoluminal cooling/warming is to instil fluid (generally saline) through an existing anatomic hollow/tubular organ adjacent to the ablation zone, in order to prevent thermal injury to the mucosa and avoid secondary perforation and/or stricture.

Biliary Cooling

Biliary cooling is performed by infusing 5% dextrose–water solution (D5W) or saline within the proximal bile ducts, in order to prevent thermal biliary injury, and avoid bile duct strictures which typically manifest 3 to 4 weeks post-procedure [18, 19]. The technique is used during heat-based ablation of central liver tumours (< 1 cm from common or left/right hepatic ducts), and particularly for lesions < 6 mm away which are at high risk of thermal injury [20].

Most authors advocate the endoscopic placement of a naso-biliary tube (5 Fr) in the major bile duct adjacent to the target lesion prior to ablation [21]. Direct percutaneous transhepatic biliary catheter placement is also possible, but technically challenging in the absence of biliary dilatation [22]. Cooled (5–8 °C) D5W or saline is infused via a pressure bag at a rate of 1–2 ml/s throughout the procedure until ablation is completed [19].

Several porcine studies have demonstrated the efficacy of biliary cooling to prevent thermal injury to the biliary epithelium and sub-epithelial glands, limiting the risk of secondary biliary stenosis [23], without negatively impacting ablation zone size [24]. In a clinical setting, the benefit of biliary cooling has mainly been demonstrated during hepatic RFA [18, 19, 21]. Ohnishi et al. compared outcomes of central liver tumours treated with RFA, with and without biliary cooling, and reported a significant reduction in biliary complication rate in the intraductal cooling group (2.5%) compared with controls (46%) [21]. Improved preservation of liver function at 6-month follow-up was also noted in the cooling group [21]. Felker et al. [19] also reported similar oncological outcomes between cooled and non-cooled-groups, suggesting that intraductal cooling does not compromise local tumour control. Experience with other ablation modalities is currently limited [22]. The main disadvantage is the small risk of complications related to endoscopic/percutaneous insertion.

Pyeloperfusion

Continuous irrigation of the collecting system has been proposed to limit the risk of unintended injury to the urothelium, which may result in urinary stricture and possibly urinoma [25–27]. The technique is used during ablation of central or medial/inferior renal tumours < 1.5 cm from the ureter/ureteropelvic junction, which is at particular risk [28].

Access to the collecting system may be obtained through an antegrade or retrograde approach [28–30]. Antegrade pyeloperfusion is performed through a standard 4 Fr nephrostomy tube, with a Foley catheter in the bladder to drain the injected fluid. Cooled D5W (2–6 °C) for RFA, or warmed saline (38–40 °C) for CA, is infused via the nephrostomy tube throughout the procedure [28, 30, 31]. There is no clear recommended flow rate in the literature. In an animal study, Isfort et al. [31] failed to protect the urothelium from MWA-mediated injury using a flow rate of 10 ml/min; however, another porcine study demonstrated significant reduction in RFA-mediated urothelial injury using manual injection at 1 ml/s [30]. The difference may reflect lower efficacy of pyeloperfusion for MWA than RFA; nevertheless, a flow rate of 1–2 ml/s appears advisable. The retrograde approach is performed using an open-ended ureteral catheter (6 Fr) endoscopically positioned by a urologist in the renal pelvis (Fig. 1) [32]. Cooled D5W/warmed saline (for RFA/CA) is continuously infused at a pressure of 80 cm H20, for a total volume of 1–2 litres depending on duration of ablation [32]. Similar to the antegrade approach, a Foley catheter is positioned in the bladder to remove the fluid. The urethral catheter may be fixed to the bladder catheter or to the patient to prevent displacement [32] and is usually removed immediately or the following day (except in high-risk cases where it may be exchanged for an internal drainage catheter and left in situ for 6–9 weeks) [33]. Although there are no comparative studies, retrograde pyeloperfusion is favoured in the literature, probably because anatomical access is less technically demanding and does not increase risk of bleeding.

The efficacy of pyeloperfusion to protect the collecting system from thermal injury, without negatively impacting ablation zone size, has been demonstrated in an animal model [30]. Several clinical studies have confirmed feasibility, safety and efficacy during RFA and CA, with a significant decrease in number of complications [28, 29, 32, 34, 35]. However, it should be emphasised that complications, especially ureteral strictures, may still occur [34, 35]. Some data suggest that pyeloperfusion does not appear to compromise oncological outcomes following

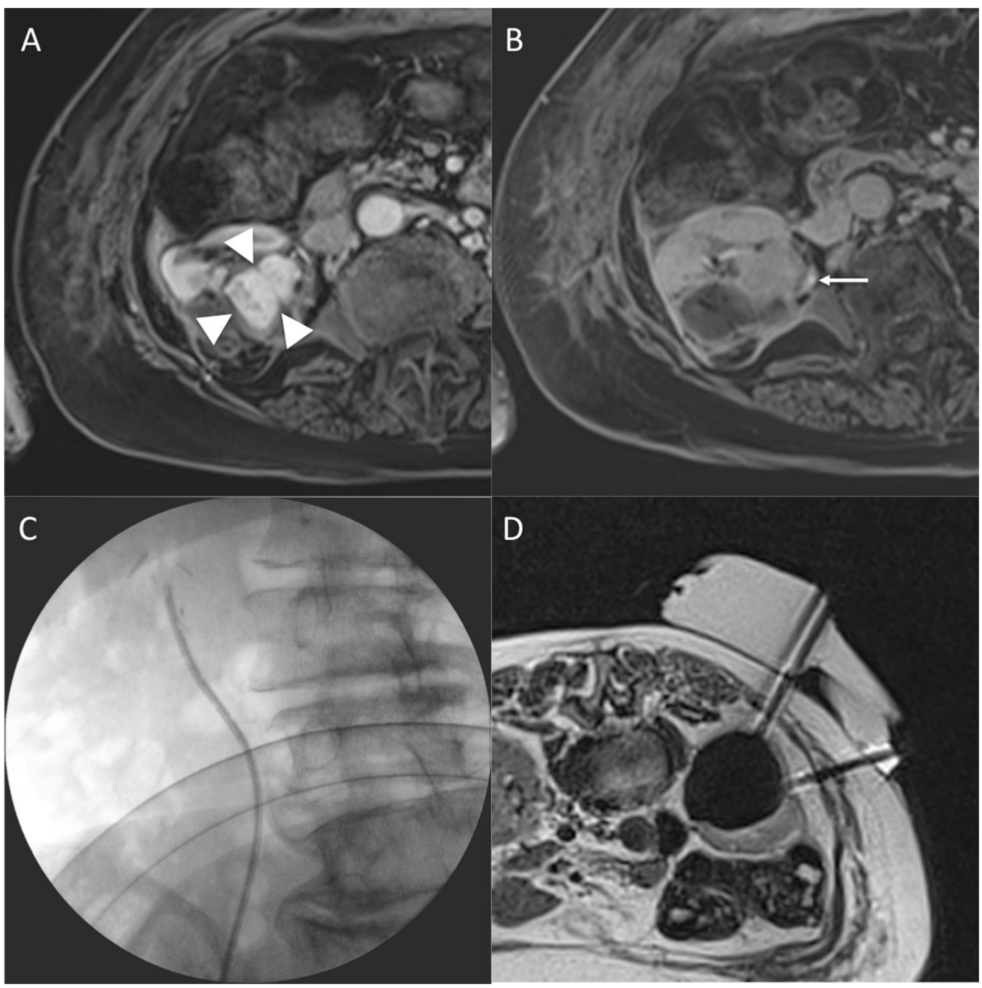

Fig. 1 Kidney cryoablation with retrograde pyeloperfusion. **A** Axial contrast-enhanced MRI (arterial phase) demonstrates recurrent postoperative clear cell carcinoma (arrowheads), referred for percutaneous cryoablation. **B** Axial contrast-enhanced MRI (delayed phase) illustrates the ureter (arrow) in close proximity to the tumour. **C** An open-ended ureteral catheter is advanced by the urologist under cystoscopic and fluoroscopic guidance. **D** MRI-guided cryoablation is then performed, while continuously warming the ureter throughout the procedure

renal RFA and CA [34, 35]. On the other hand, Breen et al. [36] recently demonstrated that cryoablation procedures associated with pyeloperfusion were less likely to experience primary technical success. Interestingly, pyeloperfusion may be applied outside renal ablation and has been sporadically reported for ureteric protection during pelvic ablation procedures [37].

Other

Theoretically, any hollow organ can be protected using endoluminal cooling or warming. Urethral warming using a dedicated closed-loop warmer device is performed during whole-gland prostate cryoablation, in order to avoid urethral sloughing/stenosis [38, 39]. Rectal warming has also been described to protect the rectal mucosa during prostate cryoablation [40]; however, the system is cumbersome with limited clinical applicability [40]. Nevertheless, the technique could be considered during ablation of complex pelvic tumours abutting the rectum. Finally, tracheal and oesophageal cooling during intrathoracic ablations has been reported, with variable efficacy [41, 42].

Organ Filling/Emptying

Certain organs may be deliberately filled or emptied in order to facilitate access to a lesion, and/or increase distance from the ablation zone. For example, Levit et al. [43] reported on 6 cases the feasibility of bile aspiration from the gallbladder during RFA of liver tumours less than 1 cm from the gallbladder wall, in order to increase distance from the ablation zone. Emptying the stomach may be useful to optimise access to left hepatic/renal lesions, particularly if the stomach is distended with gas following induction of general anaesthesia. Finally, certain organs such as the bladder may be intentionally filled, in order to displace vulnerable structures away from target lesions and enable safe ablation (Fig. 2).

Percutaneous Techniques

Probe Torqueing/Traction

Manual traction on thermo-probes may physically displace tumours away from vulnerable structures, avoiding collateral damage and thermal sink effects [33]. The technique

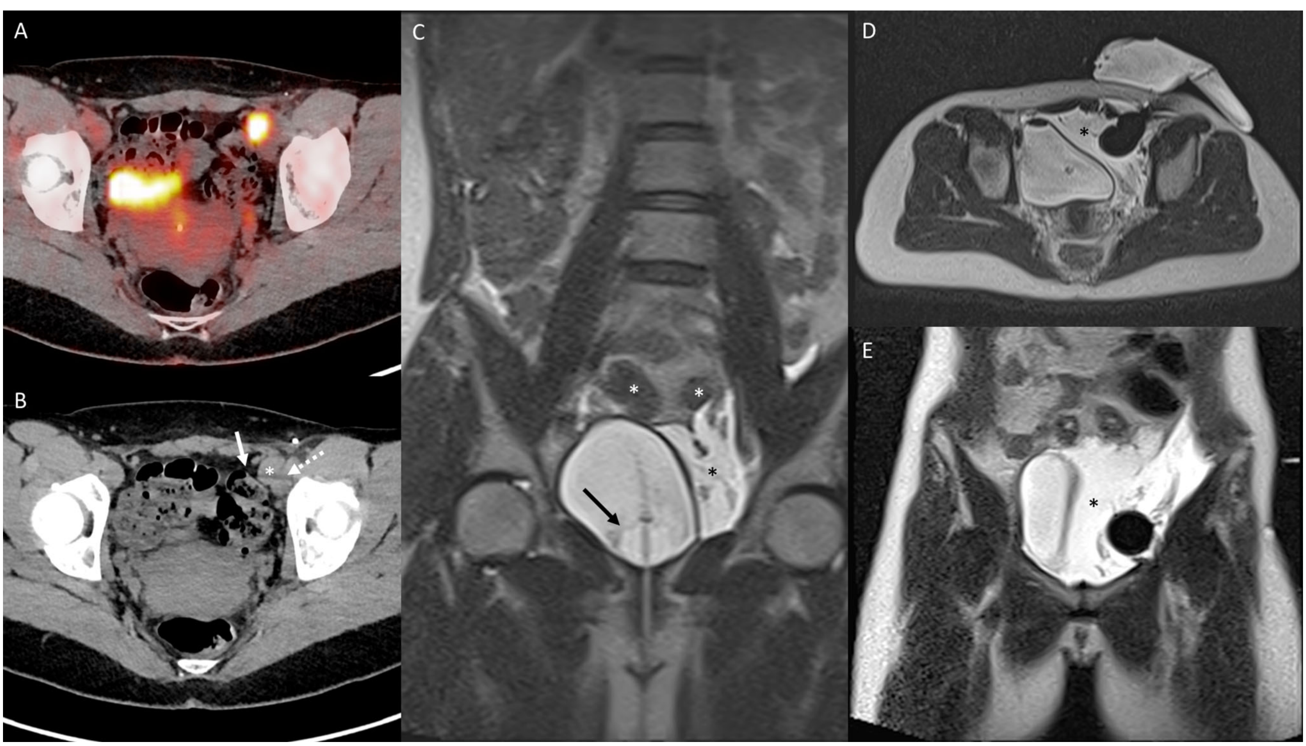

Fig. 2 MRI-guided cryoablation of a single iliac lymph node metastasis from melanoma. **A** Axial PET-CT shows an FDG avid left external iliac lymph node. **B** The lesion (asterisk) is in close vicinity to the colon (arrow) and external iliac vessels (dotted arrow). **C** A double-lumen bladder catheter (black arrow) is inserted and the bladder is filled with 1L of saline, thereby displacing the bowel (white asterisk) and facilitating subperitoneal hydrodissection (black asterisk). **D**, **E** This permits aggressive treatment of the lesion, with the ice ball (appearing as a signal void) covering the tumour with safety margins. Note extensive subperitoneal hydrodissection (black asterisk) enabled by filling the bladder

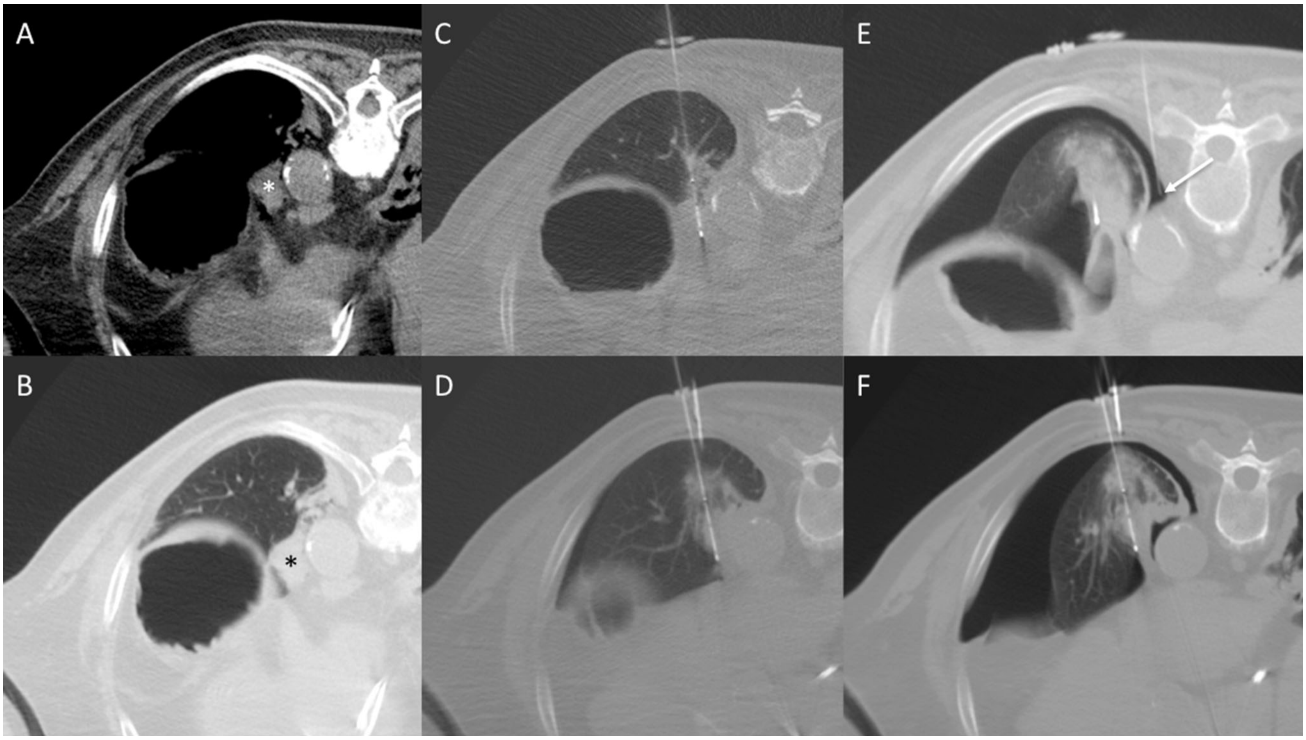

Fig. 3 Cryoablation of a primary lung cancer. **A**, **B** Axial CT scan (**A** mediastinal window; **B** lung window) illustrates a mass located close to the diaphragm, stomach and the aorta (white asterisk in **A**; black in **B**). **C** A cryoprobe is inserted inside the lesion using a posterior approach. **D** Using "stick mode" (which uses low freezing energy to cryoadhese the probe tip inside the lesion) and applying gentle traction, the probe is retracted to move the tumour 2 cm away from its initial position. **E**, **F** An additional iatrogenic pneumothorax using CO_2 is performed using a 22G needle (arrow in **E**), to increase lung mobility and optimise tumour retraction

has mainly been reported using expandable RFA and CA devices [11, 44]. With expandable electrodes, the tines firmly anchor the RFA probe within the tumour, enabling lesion mobilisation by pulling on the co-axial introducer system [6]. With cryoprobes, it is possible to freeze (cryoadhese) the probe tips within/around the tumour (using lower freezing power/"stick mode"), allowing the lesion to be retracted away from vulnerable structures prior to full-strength ablation (Fig. 3) [45]. However, care must be taken to avoid cryoprobe disengagement during the thawing phase [45]. Straight RFA/MWA needles may also be used, but serve only as levers since they are not fixed inside the lesion.

Probe torqueing/traction has mainly been described in the kidney, lung and liver [44, 46, 47]. During renal ablation, the technique may be used to displace tumours away from the bowel or ureter [47, 48], but efficacy is limited. In the few reported cases, tumour/bowel separation achieved during RFA did not exceed 8 mm [48]. In the lung, greater tumour retraction is possible due to increased tissue compliance, and lesions may be displaced greater than 1 cm. This is of particular interest for tumours adjacent to the diaphragm, mediastinum, brachial plexus and chest wall (Fig. 4) [49, 50]. An additional iatrogenic pneumothorax may also facilitate further increased tumour retraction, as the lung becomes more mobile [6].

Hydrodissection

Injection of fluid between lesions and vulnerable structures is an effective, inexpensive method of thermal protection. Feasibility and utility are supported by a wide literature base, including thoracic, abdomino-pelvic, spinal and peri-articular ablations [11, 48, 51–53]. To perform hydrodissection, a small-calibre needle (usually 20G or 22G) is introduced between the ablation zone and vulnerable surrounding organ(s) under imaging guidance, and a variable volume of fluid is injected until adequate separation (usually 1 cm) is obtained [11, 33]. Distribution of fluid depends on the precise tissue plane in which the needle tip is located, and detailed knowledge of local anatomy is essential to ensure adequate dissection [54].

Type of hydrodissection fluid is carefully selected depending on ablation modality. Due to its intrinsic electrical conductivity, saline should not be used with RFA, and instead 5% dextrose in water is preferred [11, 33, 52]. Saline may be safely used in combination with MWA, CA and laser ablation since these modalities do not risk conduction of electrical current [55–57].

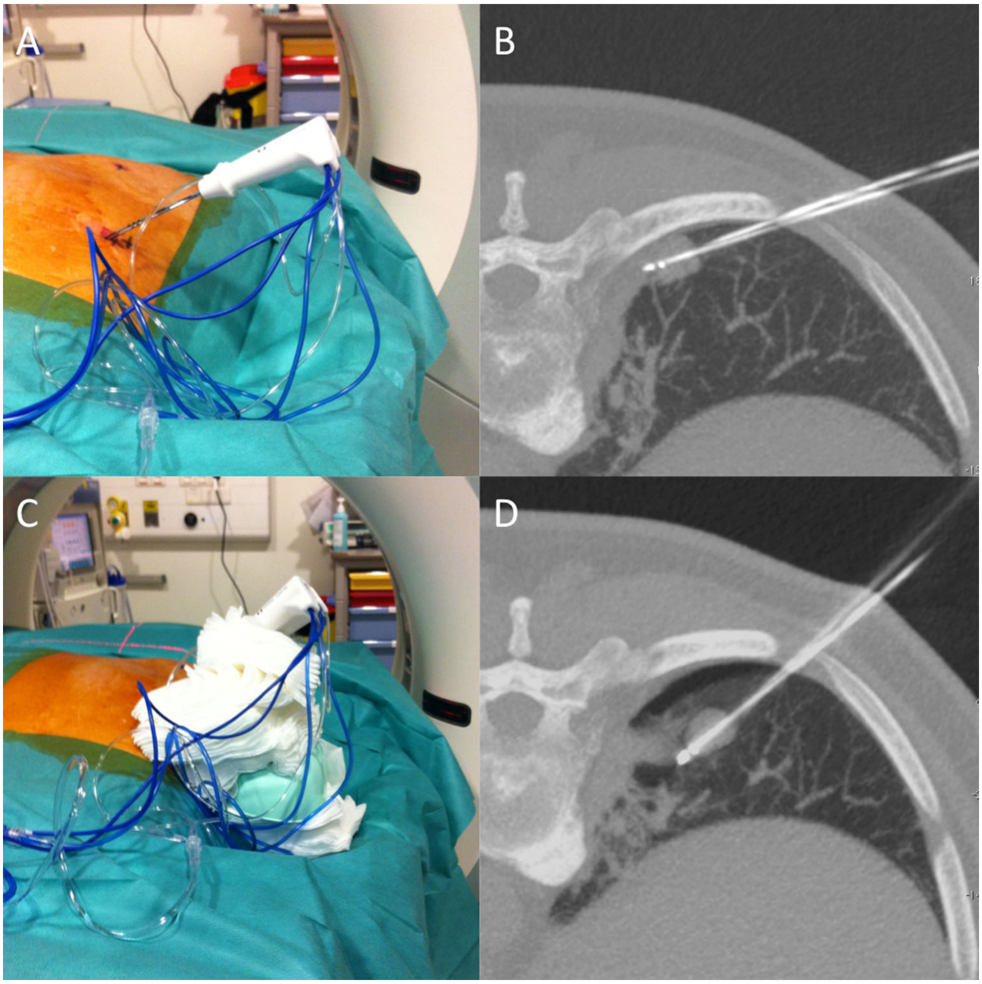

Fig. 4 Lung RFA of a subpleural metastasis. **A**, **B** Two straight probes are inserted within the pulmonary mass using a posterolateral approach. **C**, **D** To avoid unintentional chest wall/pleural injury, the two electrodes are used as a lever to displace the tumour medially and increase distance from the thoracic wall

Volume of injected fluid is highly variable, depending on the anatomic location of ablation and type of organ requiring protection, and may range from a few millilitres to more than two litres [58, 59]. As reported in the peritoneum, retroperitoneum, mediastinum and epidural space, large-volume hydrodissection is safe, since saline/D5W spreads through the tissues without inducing compressive effects [54, 59, 60]. However, care should be taken to inject as little as necessary, as very high volumes (several litres) may result in life-threatening hydro-electrolytic disorders [61].

One major advantage of hydrodissection is the ability to precisely monitor fluid distribution and organ displacement using imaging guidance (US, CT, MRI) [53, 55, 62]. Visibility with CT guidance can be significantly improved by diluting fluid with non-ionic contrast media [63]. Optimal dilution is obtained using a contrast/fluid ratio of 1:50, which facilitates good visibility without streak artefacts [60, 63]; improves differentiation between injected fluid, tumour and adjacent tissues [60, 64]; and may even outline occult anatomic structures in negative, such as small nerves [60].

Hydrodissection has several further advantages. It allows difficult-to-access lesions (mediastinum, pelvis) to be targeted by pushing away the surrounding organs (Fig. 5) [60, 65]. During US-guided procedures, hydrodissection (in the form of artificial pleural effusion/ascites) may create a clear acoustic window, enabling access to lesions in difficult-to-image locations such as the hepatic dome [54]. Hydrodissection also provides both passive and active thermal protection. Passive protection results from insulation and convection effects secondary to increased distance and fluid interposition between the ablation zone and surrounding organ(s). Active protection is performed via continuous injection of warmed/cooled fluid during ablation [11]. Efficacy may be monitored using a thermosensor placed next to sensitive structures, enabling control over local temperature in real time [11]. This is

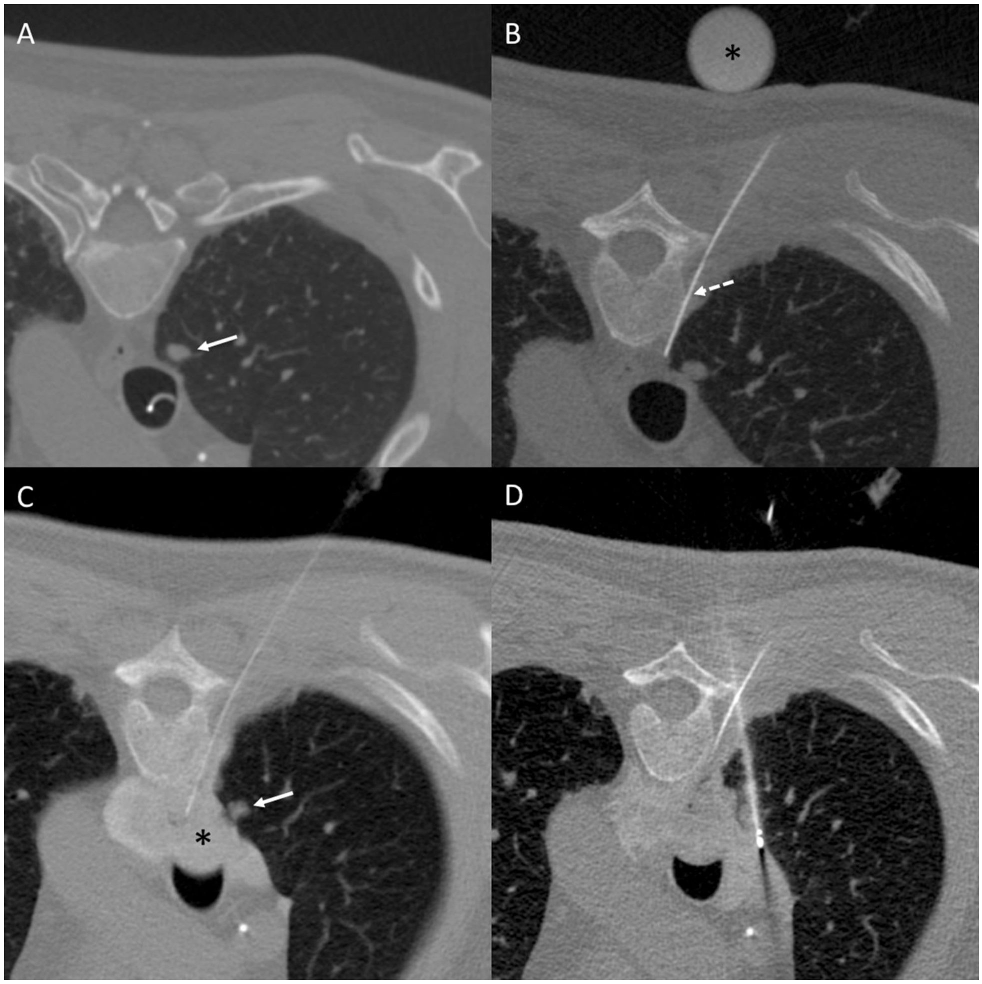

Fig. 5 RFA of a small lung metastasis. **A** Axial CT scan demonstrates a small nodule (arrow) located close to the trachea, difficult to target. **B** A 22G spinal needle is advanced in the posterior mediastinum using a paravertebral approach (dotted arrow). Proper dilution of contrast within D5W is checked by putting the syringe on the skin of the patient (black asterisk). **C** Injection of D5W mixed with contrast media (black asterisk) enables lateral displacement of the tumour (arrow) away from the mediastinum, creating a safer and more straightforward access pathway. **D** An RFA probe is more easily introduced, distant from the trachea, and avoids any thermal injury to the large airways

particularly helpful for complex ablations, e.g. in the spine (Fig. 6) [57, 66]. Finally, hydrodissection can help reduce thermal sink effects by displacing vessels away from the ablation zone [60].

Efficacy of hydrodissection has predominantly been documented for kidney and liver ablations. Using injection volumes of 250–500 ml, structures such as the colon, small bowel and lumbar muscles can be effectively protected during renal ablation [33, 48, 67]. Oncological results do not appear to be compromised, although the literature remains scarce [68]. During liver ablation, artificial ascites (peritoneal hydrodissection) is widely performed to protect the diaphragm and intra-abdominal organs (Fig. 7) [54, 58]. In a study of 44 lesions located in the liver dome, Kang et al. [69] showed that artificial ascites significantly mitigated the risk of diaphragmatic thermal injury without decreasing oncological efficacy. Similar results have been reported in the spine, where hydrodissection was successfully utilised during laser ablation of osteoid osteomas close to the spinal cord without negatively impacting local efficacy [59].

Hence, hydrodissection is a safe, inexpensive thermoprotective technique which facilitates protection of vulnerable surrounding organs in most locations. Technical failure is rare, but may occur in the presence of post-operative adhesions, or if the fluid disperses away from the injection site [11, 48, 70].

Gas Dissection

Thermal protection by percutaneous injection of room air or CO_2 is possible [11, 48, 66, 71]. However,

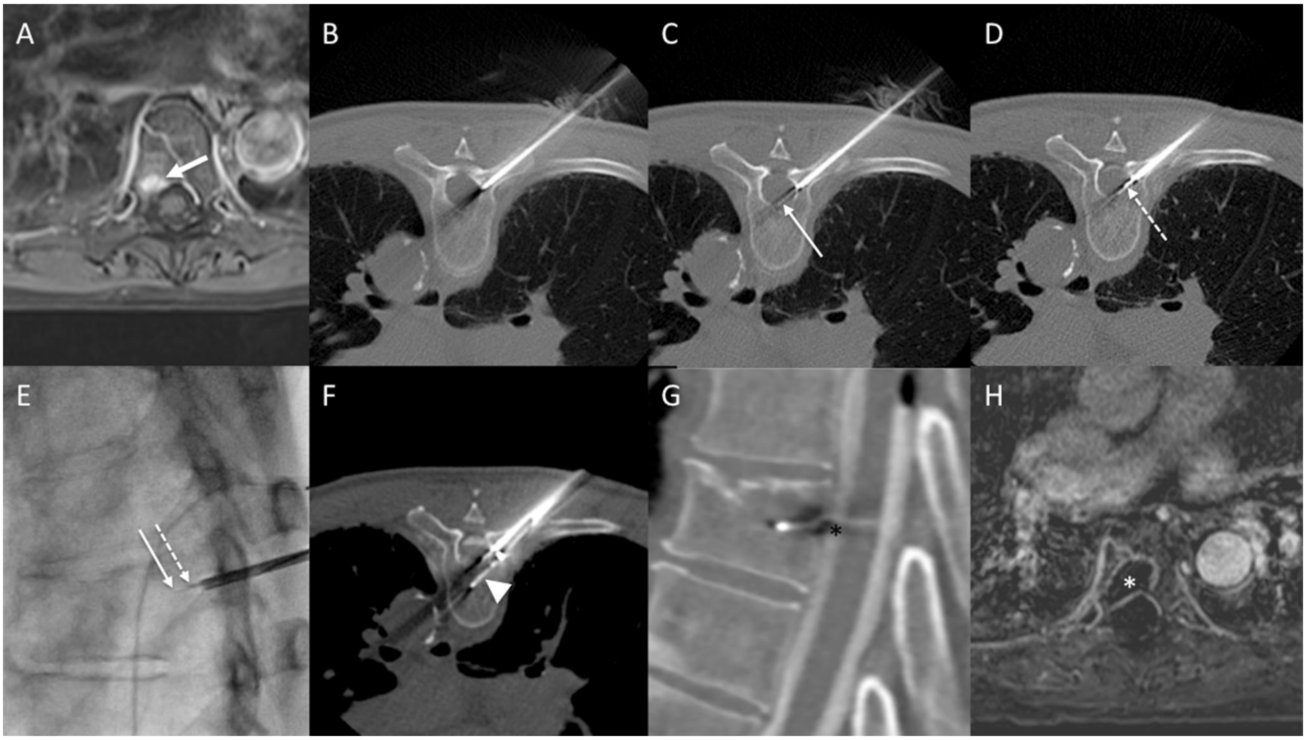

Fig. 6 RFA of a small spinal metastasis. **A** Axial contrast-enhanced MRI shows a metastasis from thyroid carcinoma abutting the posterior wall of the vertebral body (arrow). **B** A 13G bone trocar is advanced towards the canal using a posterolateral approach. **C** A 28G thermosensor is carefully advanced inside the epidural space (arrow). **D** An additional 22G spinal needle is inserted co-axially, parallel to the thermosensor inside the bone trocar (dotted arrow), to perform epidural hydrodissection. **E** Lateral fluoroscopy illustrates both the spinal needle (dotted arrow) and thermosensor (arrow). **F** A bipolar RFA probe is inserted within the lesion (arrowhead). **G** Hydrodissection (black asterisk) is performed to create a safe distance between the spinal cord and posterior vertebral wall. The thermosensor continuously monitors local temperature throughout the ablation phase, increasing procedural safety and guiding need for active cooling using hydrodissection. **H** Axial contrast-enhanced MRI with subtraction at one-month follow-up shows complete devascularisation of the tumour, without any damage to the spinal cord

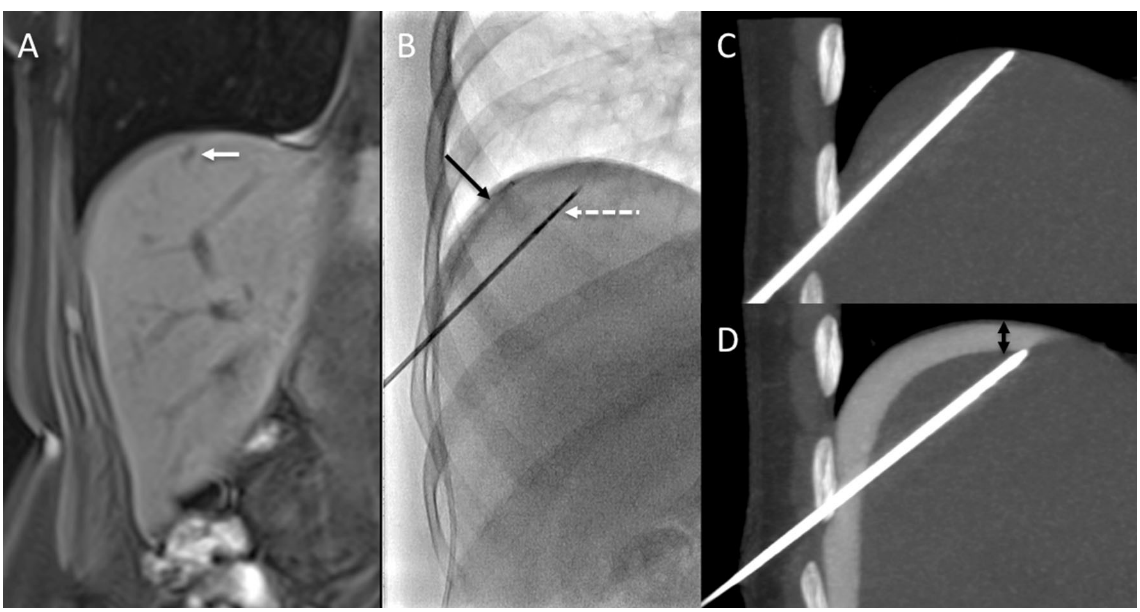

Fig. 7 Artificial ascites. **A** Coronal T1-weighted MRI demonstrates a small liver metastasis (arrow) abutting the diaphragm. **B** Anteroposterior fluoroscopic view shows the microwave antenna in position (dotted white arrow). A 5F catheter (black arrow) is positioned in the peritoneum between the liver dome and the diaphragm. **C** Coronal CT scan before and **D** after injection of 100 ml diluted contrast in saline demonstrates generation of a safe distance between the ablation zone and diaphragm (double black arrow)

carbodissection is the preferred method due to the much lower risk of symptomatic gas embolism than with room air, should gas enter the intravascular space [66, 72]. Feasibility and safety have been widely demonstrated during laparoscopy in various locations including the pleura, peritoneum and retroperitoneum [72].

CO_2 dissection can be easily performed using the same device as for CO_2 angiography [73]. Following placement of a small-calibre needle in the desired anatomic space, the CO_2 injection system is connected to a CO_2 bottle on the one side and the needle on the other side [11, 73]. Following test injection of a small volume to confirm correct distribution, gas insufflation is continued until desired tumour–organ separation is achieved. CO_2 is easily seen on CT, as it appears completely hypoattenuating (like air) [11, 73]; however, US-guided carbodissection is not recommended due to the poor acoustic window following CO_2 injection [11].

Required injection volume to achieve sufficient protection is highly variable and depends on the anatomic location of injection and rate of reabsorption. In one study, involving 37 patients, volume ranged from 10 ml in the epidural space to 1500 ml in the abdomen [73]. In practice, it is usually necessary to re-inject CO_2 regularly because it is quickly resorbed; careful monitoring with intermittent CT during ablation is therefore mandatory to ensure adequate protection throughout the procedure.

Similar to hydrodissection, CO_2 injection may be used to enable access to lesions (via organ displacement) and/or facilitate thermal protection (Fig. 8) [73, 74]. CO_2 is an excellent thermal insulator, superior to air [73], and offers effective protection not only by pushing vulnerable organs away, but also by creating a thermal shield insulating the organ from RFA, CA, MW or laser energy [11]. One limitation is that gas distributes in the non-dependent portions of the targeted anatomic space [73]. Hence, CO_2

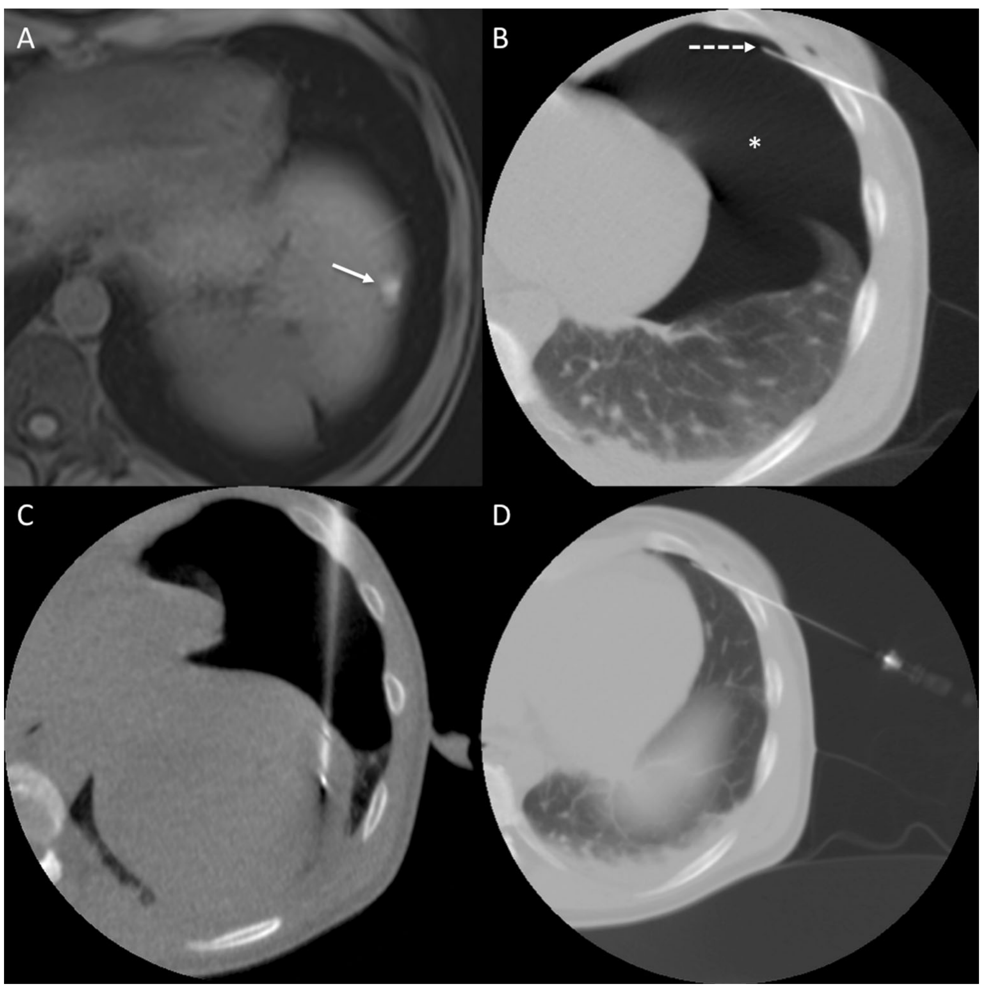

Fig. 8 Cryoablation of a diaphragmatic nodule of endometriosis. **A** Axial unenhanced T1 W MRI shows a hyperintense diaphragmatic nodule (arrow). **B** Iatrogenic pneumothorax (asterisk) is created following CO_2 injection using a 22G spinal needle (dotted arrow), in order to obtain safe access to the lesion. **C** A 17G cryoprobe is inserted inside the lesion without damaging the lung. **D** CO_2 is re-aspirated at the end of the procedure

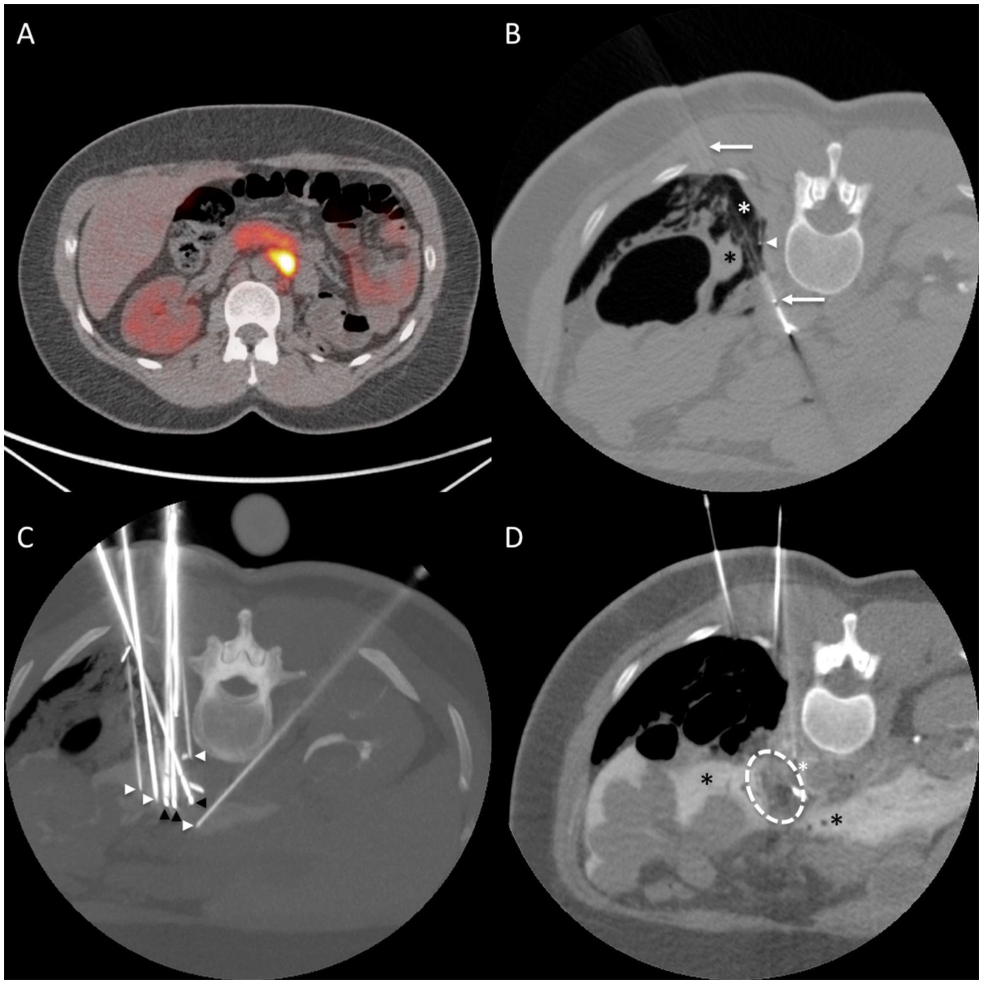

Fig. 9 Cryoablation of a solitary retroperitoneal metastasis from malignant pheochromocytoma. **A** Axial PET-CT shows an avid metastasis located close to the aorta, pancreas and small bowel. **B** Carbodissection (white asterisk) is performed through a 22G spinal needle (arrowhead) to push away the colon (black asterisk) and create a safe pathway for cryoprobe insertion (arrow). **C** In total, 3 cryoprobes (black arrowheads) and a further 4 hydrodissection needles (white arrowheads) were inserted. **D** Following additional hydrodissection, complete lesion coverage with the ice ball (dotted circle) was possible, while mitigating the heat sink effect from the aorta and avoiding any contact with the bowel (white and black asterisks in **D**)

protection should be preferentially used when the vulnerable structure is anterior to the tumour [39]. Carbodissection can be combined with hydrodissection for complex cases (Fig. 9).

Dissection with Other Agents

One of the major limitations of hydro-/carbodissection is diffusion of fluid/gas away from the injection site during the procedure. Several novel agents have been developed to overcome this issue and create a durable interface between the tumour and surrounding organ(s). Most available publications are small case series, and there is currently insufficient evidence to support routine implementation.

Autologous blood has been described as an inexpensive and effective agent to artificially increase the distance between the prostate and rectum during prostatic CA [75]. As injected blood turns into clot, a long-lasting widening of the inter-prostatorectal space is achieved. Fibrillar collagen, an absorbable bovine haemostatic agent, has been used in 3 cases of liver ablation and facilitated significant (15–21 mm) durable separation of the colon and stomach [76]. Similarly, injection of a mixture of hyaluronic acid gel and contrast successfully separated the gastrointestinal tract in 11 patients undergoing liver ablation [77].

Novel thermo-protective gels have also emerged in the market. Poloxamer 407 (P407) is a non-ionic surfactant consisting of tri-block co-polymers, initially developed as a drug carrier, which can be injected as a liquid at room temperature, and transitions into a semi-solid gel at body temperature [78, 79]. This creates a durable barrier throughout the ablation, which is gradually resorbed post-procedure. According to ex vivo MWA studies, 5-mm-thick gel results in a temperature difference of 18 °C between both sides of the gel [78]. The mechanism of action seems to be predominantly heat conduction, rather than convection more associated with hydrodissection [79]. Efficacy/safety of the technique has currently only been demonstrated in animal studies [80, 81].

Balloon Interposition

The principle of balloon interposition is to insert an angioplasty or oesophageal balloon between the tumour and vulnerable adjacent structure [11, 33, 48]. Although there are different insertion methods, most authors advocate use of a sheath over a 0.035-inch stiff wire [11, 33, 48]. The sheath and co-axially inserted balloon are inserted into the space between the tumour and adjacent organ under imaging guidance, and the balloon is exposed by carefully retracting the sheath. It is convenient to initially insert the sheath/balloon beyond the desired position, since balloon retraction is easier than advancement [48]. Once in position, the balloon is inflated with air, facilitating both physical displacement and creation of a thermal barrier due to the insulating properties of air [11, 48].

The majority of current experience comes from renal ablation, where balloon interposition has been used to displace bowel away from the ablation zone [47, 82]. The technique may be effective even when other methods such as hydro-/carbodissection have failed [47]. Besides complexity of insertion, the major drawback is the tendency of the balloon to slide away from its initial position [48]. Hence, several balloons are usually necessary to achieve satisfactory protection (Fig. 10). Most authors therefore recommend balloon interposition as a second-line thermoprotective strategy [11, 33, 48].

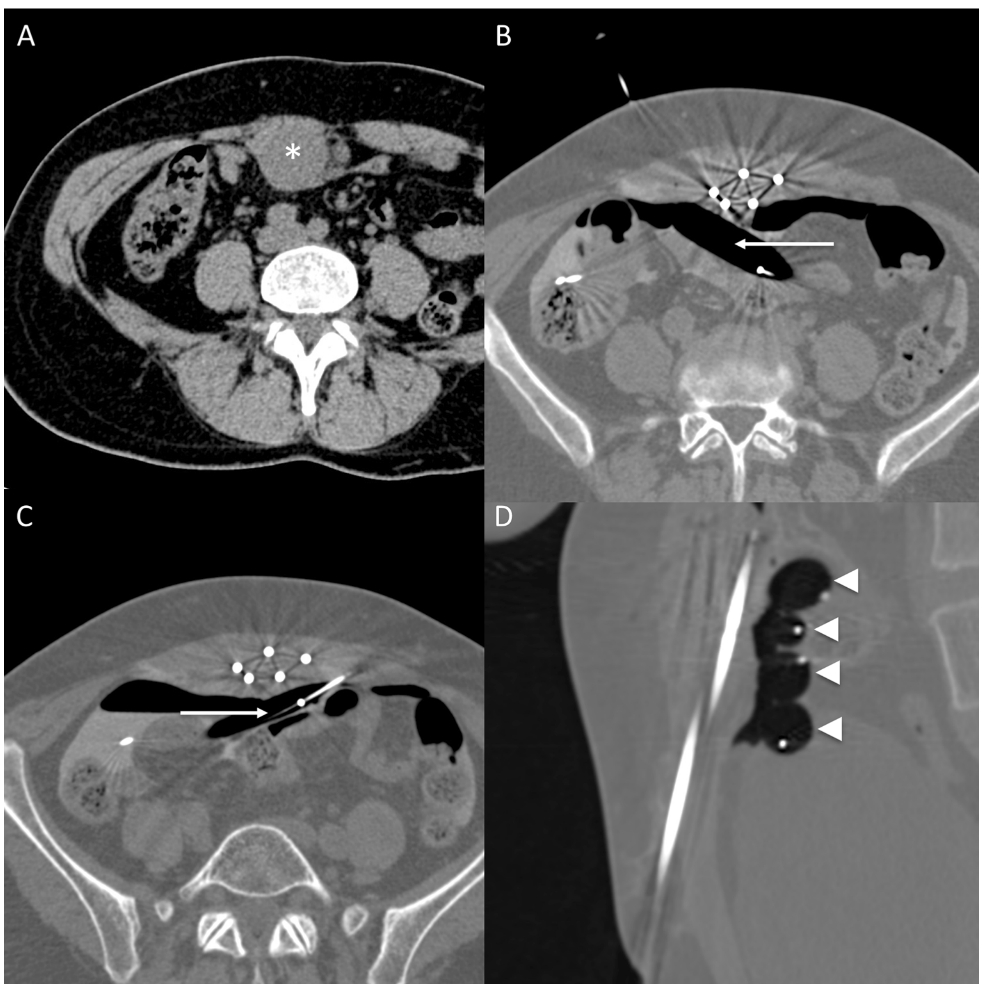

Fig. 10 Cryoablation of a large solitary metastasis from ovarian cancer. **A** The lesion is intramuscular and protrudes towards the peritoneal cavity (white asterisk). **B**, **C** In this case, both hydrodissection and carbodissection failed to protect the underlying small bowel. Several balloons were therefore inserted to create a safe distance between the ice ball and bowel (arrows in **B**, **C**). **D** In total, 4 balloons (white arrowheads on sagittal CT scan) were required to protect the bowel loops

Conclusion

A wide variety of thermo-protective methods may used to protect the surrounding organs during percutaneous thermal ablation. Interventional radiologists should understand how and when to use these techniques, in order to limit risk of complications and enable treatment of lesions that would otherwise be considered unsuitable for ablation.

Compliance with Ethical Standards

Conflict of interest Julien Garnon is a proctor for BTG-Galil and has received fees for oral presentations for Toshiba and Medtronic. Roberto Luigi Cazzato has received fees for oral presentations for Medtronic. Guillaume Koch is a proctor for BTG-Galil.

References

1. de Baère T, Aupérin A, Deschamps F, Chevallier P, et al. Radiofrequency ablation is a valid treatment option for lung metastases: experience in 566 patients with 1037 metastases. Ann Oncol. 2015;26(5):987–91. https://doi.org/10.1093/annonc/mdv037.
2. Meijerink MR, Puijk RS, van Tilborg AAJM, Henningsen KH, et al. Radiofrequency and microwave ablation compared to systemic chemotherapy and to partial hepatectomy in the treatment of colorectal liver metastases: a systematic review and meta-analysis. Cardiovasc Interv Radiol. 2018. https://doi.org/10.1007/s00270-018-1959-3.
3. Thompson RH, Atwell T, Schmit G, Lohse CM, et al. Comparison of partial nephrectomy and percutaneous ablation for cT1 renal masses. Eur Urol. 2015;67(2):252–9. https://doi.org/10.1016/j.eururo.2014.07.021.
4. Garnon J, Koch G, Caudrelier J, Tsoumakidou G, et al. Expanding the borders: image- guided procedures for the treatment of musculoskeletal tumors. Diagn Interv Imaging. 2017;98(9):635–44. https://doi.org/10.1016/j.diii.2017.07.009.
5. Welch BT, Callstrom MR, Carpenter PC, Wass CT, et al. A single-institution experience in image-guided thermal ablation of adrenal gland metastases. J Vasc Interv Radiol. 2014;25(4):593–8. https://doi.org/10.1016/j.jvir.2013.12.013.
6. Palussière J, Canella M, Cornelis F, Catena V, et al. Retrospective review of thoracic neural damage during lung ablation—what the interventional radiologist needs to know about neural thoracic anatomy. Cardiovasc Interv Radiol. 2013;36(6):1602–13. https://doi.org/10.1007/s00270-013-0597-z.
7. Jeong YS, Kim SH, Lee JM, Lee JY, et al. Gastrointestinal tract complications after hepatic radiofrequency ablation: CT prediction for major complications. Abdom Radiol (NY). 2018;43(3):583–92. https://doi.org/10.1007/s00261-017-1239-8.
8. Kim HJ, Park BK, Park JJ, Kim CK. CT-guided radiofrequency ablation of T1a renal cell carcinoma in Korea: mid-term outcomes. Korean J Radiol. 2016;17(5):763–70. https://doi.org/10.3348/kjr.2016.17.5.763.
9. Goldberg SN, Ahmed M, Gazelle GS, Kruskal JB, et al. Radiofrequency thermal ablation with NaCl solution injection: effect of electrical conductivity on tissue heating and coagulation-phantom and porcine liver study. Radiology. 2001;219(1):157–65.
10. Gervais DA, McGovern FJ, Arellano RS, McDougal WS, et al. Radiofrequency ablation of renal cell carcinoma: part 1. Indications, results, and role in patient management over a 6-year period and ablation of 100 tumors. AJR Am J Roentgenol. 2005;185(1):64–71.
11. Tsoumakidou G, Buy X, Garnon J, Enescu J, et al. Percutaneous thermal ablation: how to protect the surrounding organs. Tech Vasc Interv Radiol. 2011;14(3):170–6. https://doi.org/10.1053/j.tvir.2011.02.009.
12. Pereira PL, Masala S. Cardiovascular and Interventional Radiological Society of Europe (CIRSE), Standards of practice: guidelines for thermal ablation of primary and secondary lung tumors. Cardiovasc Interv Radiol. 2012;35(2):247–54. https://doi.org/10.1007/s00270-012-0340-1.
13. Callstrom MR, York JD, Gaba RC, Gemmete JJ, et al. Research reporting standards for image-guided ablation of bone and soft tissue tumors. J Vasc Interv Radiol. 2009;20(12):1527–40. https://doi.org/10.1016/j.jvir.2009.08.009.
14. Gervais DA, Goldberg SN, Brown DB, Soulen MC, et al. Society of Interventional Radiology position statement on percutaneous radiofrequency ablation for the treatment of liver tumors. J Vasc Interv Radiol. 2009;20(1):3–8. https://doi.org/10.1016/j.jvir.2008.09.007.
15. de Kerviler E, Guermazi A, Gossot D, Cazals-Hatem D, et al. Use of an abdominal compression device for CT-guided biopsy of enlarged abdominal or pelvic lymph nodes. J Vasc Interv Radiol. 1998;9(2):353–7.
16. Dachman AH. A biopsy compression device for use in cross-sectional or fluoroscopic imaging. AJR Am J Roentgenol. 1998;171(3):703–5.
17. Tuncali K, Morrison PR, Tatli S, Silverman SG. MRI-guided percutaneous cryoablation of renal tumors: use of external manual displacement of adjacent bowel loops. Eur J Radiol. 2006;59(2):198–202.
18. Ogawa T, Kawamoto H, Kobayashi Y, Nakamura S, et al. Prevention of biliary complication in radiofrequency ablation for hepatocellular carcinoma-Cooling effect by endoscopic nasobiliary drainage tube. Eur J Radiol. 2010;73(2):385–90. https://doi.org/10.1016/j.ejrad.2008.10.021.
19. Felker ER, Lee-Felker SA, Ajwichai K, Tan N, et al. Radiofrequency ablation of central liver tumors reduces biliary injuries. AJR Am J Roentgenol. 2015;204(6):1329–35. https://doi.org/10.2214/AJR.14.13788.
20. Künzli BM, Abitabile P, Maurer CA. Radiofrequency ablation of liver tumors: Actual limitations and potential solutions in the future. World J Hepatol. 2011;3(1):8–14. https://doi.org/10.4254/wjh.v3.i1.8.
21. Ohnishi T, Yasuda I, Nishigaki Y, Hayashi H, et al. Intraductal chilled saline perfusion to prevent bile duct injury during percutaneous radiofrequency ablation for hepatocellular carcinoma. J Gastroenterol Hepatol. 2008;23(8 Pt 2):e410–5.
22. Li X, Yu J, Liang P, Yu X, et al. Ultrasound-guided percutaneous microwave ablation assisted by three-dimensional visualization operative treatment planning system and percutaneous transhepatic cholangial drainage with intraductal chilled saline perfusion for larger hepatic hilum hepatocellular ($D \geq 3$ cm): preliminary results. Oncotarget. 2017;8(45):79742–9. https://doi.org/10.18632/oncotarget.19275.
23. Raman SS, Aziz D, Chang X, Ye M, et al. Minimizing central bile duct injury during radiofrequency ablation: use of intraductal chilled saline perfusion–initial observations from a study in pigs. Radiology. 2004;232(1):154–9.
24. Jersenius U, Arvidsson D, Lindholm J, Anttila S, et al. Radiofrequency ablation in the liver close to the bile ducts: can intraductal cooling offer protection? Surg Endosc. 2005;19(4):546–50.
25. Janzen NK, Perry KT, Han KR, Kristo B, et al. The effects of intentional cryoablation and radio frequency ablation of renal

tissue involving the collecting system in a porcine model. J Urol. 2005;173(4):1368–74.
26. Johnson DB, Saboorian MH, Duchene DA, Ogan K, et al. Nephrectomy after radiofrequency ablation-induced ureteropelvic junction obstruction: potential complication and long-term assessment of ablation adequacy. Urology. 2003;62(2):351–2.
27. Chen SH, Mouraviev V, Raj GV, Marguet CG, et al. Ureteropelvic junction obliteration resulting in nephrectomy after radiofrequency ablation of small renal cell carcinoma. Urology. 2007;69(5):982.e3–5.
28. West B, Keheila M, Smith JC, Erskine A, et al. Efficacy of antegrade and retrograde warm saline pyeloperfusion during renal cryoablation for ureteral preservation. Turk J Urol. 2018;44(2):142–7. https://doi.org/10.5152/tud.2017.44380.
29. Wah TM, Koenig P, Irving HC, Gervais DA, et al. Radiofrequency ablation of a central renal tumor: protection of the collecting system with a retrograde cold dextrose pyeloperfusion technique. J Vasc Interv Radiol. 2005;16(11):1551–5.
30. Hwang SI, Cho JY, Kim SH, Jun SR, et al. Protection of the renal collecting system during radiofrequency ablation with antegrade cold dextrose infusion. Radiology. 2010;256(3):759–66. https://doi.org/10.1148/radiol.10091220.
31. Isfort P, Penzkofer T, Tanaka T, Bruners P, et al. Efficacy of antegrade pyeloperfusion to protect the renal pelvis in kidney microwave ablation using an in vivo swine model. Invest Radiol. 2013;48(12):863–8. https://doi.org/10.1097/RLI.0b013e3182a2af82.
32. Cantwell CP, Wah TM, Gervais DA, Eisner BH, et al. Protecting the ureter during radiofrequency ablation of renal cell cancer: a pilot study of retrograde pyeloperfusion with cooled dextrose 5% in water. J Vasc Interv Radiol. 2008;19(7):1034–40. https://doi.org/10.1016/j.jvir.2008.04.005.
33. Mauri G, Nicosia L, Varano GM, Bonomo G, et al. Tips and tricks for a safe and effective image-guided percutaneous renal tumour ablation. Insights Imaging. 2017;8(3):357–63. https://doi.org/10.1007/s13244-017-0555-4.
34. Eswara JR, Gervais DA, Mueller PR, Arellano RS, et al. Renal radiofrequency ablation with pyeloperfusion. Int J Urol. 2015;22(1):131–2. https://doi.org/10.1111/iju.12625.
35. Dai Y, Covarrubias D, Uppot R, Arellano RS. Image-guided percutaneous radiofrequency ablation of central renal cell carcinoma: assessment of clinical efficacy and safety in 31 tumors. J Vasc Interv Radiol. 2017;28(12):1643–50. https://doi.org/10.1016/j.jvir.2017.05.006.
36. Breen DJ, King AJ, Patel N, Lockyer R, Hayes M. Image-guided cryoablation for sporadic renal cell carcinoma: three- and 5-year outcomes in 220 patients with biopsy-proven renal cell carcinoma. Radiology. 2018;7:180249. https://doi.org/10.1148/radiol.2018180249.
37. Butros SR, DelCarmen MG, Uppot RN, Arellano RS. Image-guided percutaneous thermal ablation of metastatic pelvic tumor from gynecologic malignancies. Obstet Gynecol. 2014;123(3):500–5. https://doi.org/10.1097/AOG.0000000000000133.
38. Saliken JC, Donnelly BJ, Rewcastle JC. The evolution and state of modern technology for prostate cryosurgery. Urology. 2002;60(2 Suppl 1):26–33.
39. Barqawi AB, Huebner E, Krughoff K, O'Donnell CI. Prospective outcome analysis of the safety and efficacy of partial and complete cryoablation in organ-confined prostate cancer. Urology. 2018;112:126–31. https://doi.org/10.1016/j.urology.2017.10.029.
40. Gangi A, Tsoumakidou G, Abdelli O, Buy X, et al. Percutaneous MR-guided cryoablation of prostate cancer: initial experience. Eur Radiol. 2012;22(8):1829–35. https://doi.org/10.1007/s00330-012-2411-8.
41. Hiraki T, Yasui K, Mimura H, Gobara H, et al. Radiofrequency ablation of metastatic mediastinal lymph nodes during cooling and temperature monitoring of the tracheal mucosa to prevent thermal tracheal damage: initial experience. Radiology. 2005;237(3):1068–74.
42. Sohara H, Satake S, Takeda H, Yamaguchi Y, et al. Prevalence of esophageal ulceration after atrial fibrillation ablation with the hot balloon ablation catheter: what is the value of esophageal cooling? J Cardiovasc Electrophysiol. 2014;25(7):686–92. https://doi.org/10.1111/jce.12394.
43. Levit E, Bruners P, Günther RW, Mahnken AH. Bile aspiration and hydrodissection to prevent complications in hepatic RFA close to the gallbladder. Acta Radiol. 2012;53(9):1045–8. https://doi.org/10.1258/ar.2012.120190.
44. Froemming A, Atwell T, Farrell M, Callstrom M, et al. Probe retraction during renal tumor cryoablation: a technique to minimize direct ureteral injury. J Vasc Interv Radiol. 2010;21(1):148–51. https://doi.org/10.1016/j.jvir.2009.09.014.
45. Garnon J, Koch G, Ramamurthy N, Caudrelier J, et al. A pitfall of cryoadhesional displacement during cryoablation of lung metastasis to require modification of triple-freeze protocol. Cardiovasc Interv Radiol. 2016;39(6):960–4. https://doi.org/10.1007/s00270-016-1312-7.
46. Kambadakone A, Baliyan V, Kordbacheh H, Uppot RN, et al. Imaging guided percutaneous interventions in hepatic dome lesions: tips and tricks. World J Hepatol. 2017;9(19):840–9. https://doi.org/10.4254/wjh.v9.i19.840.
47. Ginat DT, Saad W, Davies M, Walman D, et al. Bowel displacement for CT-guided tumor radiofrequency ablation: techniques and anatomic considerations. J Endourol. 2009;23(8):1259–64. https://doi.org/10.1089/end.2008.0668.
48. Ginat DT, Saad WE. Bowel displacement and protection techniques during percutaneous renal tumor thermal ablation. Tech Vasc Interv Radiol. 2010;13(2):66–74. https://doi.org/10.1053/j.tvir.2010.02.002.
49. Alexander ES, Hankins CA, Machan JT, Healey TT, et al. Rib fractures after percutaneous radiofrequency and microwave ablation of lung tumors: incidence and relevance. Radiology. 2013;266(3):971–8. https://doi.org/10.1148/radiol.12120933.
50. Alberti N, Ferretti G, Buy X, Desjardin M, et al. Diaphragmatic hernia after lung percutaneous radiofrequency ablation: incidence and risk factors. Cardiovasc Interv Radiol. 2014;37(6):1516–22. https://doi.org/10.1007/s00270-014-0854-9.
51. Farrell MA, Charboneau JW, Callstrom MR, Reading CC, et al. Paranephric water instillation: a technique to prevent bowel injury during percutaneous renal radiofrequency ablation. AJR Am J Roentgenol. 2003;181(5):1315–7.
52. Arellano RS, Garcia RG, Gervais DA, Mueller PR. Percutaneous CT-guided radiofrequency ablation of renal cell carcinoma: efficacy of organ displacement by injection of 5% dextrose in water into the retroperitoneum. AJR Am J Roentgenol. 2009;193(6):1686–90. https://doi.org/10.2214/AJR.09.2904.
53. Liu CH, Yu CY, Chang WC, Dai MS, et al. Computed tomographic-guided percutaneous radiofrequency ablation with hydrodissection of hepatic malignancies in the subcapsular location: evaluation of safety and technical efficacy. J Chin Med Assoc. 2016;79(2):93–100. https://doi.org/10.1016/j.jcma.2015.07.013.
54. Bhagavatula SK, Chick JF, Chauhan NR, Shyn PB. Artificial ascites and pneumoperitoneum to facilitate thermal ablation of liver tumors: a pictorial essay. Abdom Radiol (NY). 2017;42(2):620–30. https://doi.org/10.1007/s00261-016-0910-9.
55. Cheng Z, Yu X, Han Z, Liu F, et al. Ultrasound-guided hydrodissection for assisting percutaneous microwave ablation of renal cell carcinomas adjacent to intestinal tracts: a preliminary clinical study. Int J Hyperth. 2018;34(3):315–20. https://doi.org/10.1080/02656736.2017.1338362.
56. Georgiades CS, Rodriguez R. Efficacy and safety of percutaneous cryoablation for stage 1A/B renal cell carcinoma: results of a

prospective, single-arm, 5-year study. Cardiovasc Interv Radiol. 2014;37(6):1494–9. https://doi.org/10.1007/s00270-013-0831-8.
57. Tsoumakidou G, Koch G, Caudrelier J, Garnon J, et al. Image-guided spinal ablation: a review. Cardiovasc Interv Radiol. 2016;39(9):1229–38. https://doi.org/10.1007/s00270-016-1402-6.
58. Asvadi NH, Anvari A, Uppot RN, Thabet A, et al. CT-guided percutaneous microwave ablation of tumors in the hepatic dome: assessment of efficacy and safety. J Vasc Interv Radiol. 2016;27(4):496–502. https://doi.org/10.1016/j.jvir.2016.01.010 **(quiz 503)**.
59. Tsoumakidou G, Thénint MA, Garnon J, Buy X, et al. Percutaneous image-guided laser photocoagulation of spinal osteoid osteoma: a single-institution series. Radiology. 2016;278(3): 936–43. https://doi.org/10.1148/radiol.2015150491.
60. Garnon J, Koch G, Caudrelier J, Ramamurthy N, et al. Percutaneous image-guided cryoablation of challenging mediastinal lesions using large-volume hydrodissection: technical considerations and outcomes. Cardiovasc Interv Radiol. 2016; 39(11):1636–43. https://doi.org/10.1007/s00270-016-1396-0.
61. Jiang L, Krishnasamy V, Varano GM, Wood BJ. Hyponatremia following high-volume D5W hydrodissection during thermal ablation. Cardiovasc Interv Radiol. 2016;39:146–9.
62. Cazzato RL, Garnon J, Shaygi B, Tsoumakidou G, et al. How to perform a routine cryoablation under MRI guidance. Top Magn Reson Imaging. 2018;27(1):33–8. https://doi.org/10.1097/RMR.0000000000000158.
63. DeBenedectis CM, Beland MD, Dupuy DE, Mayo-Smith WW. Utility of iodinated contrast medium in hydrodissection fluid when performing renal tumor ablation. J Vasc Interv Radiol. 2010;21(5):745–7. https://doi.org/10.1016/j.jvir.2010.01.022.
64. Campbell C, Lubner MG, Hinshaw JL, Muñoz del Rio A, et al. Contrast media-doped hydrodissection during thermal ablation: optimizing contrast media concentration for improved visibility on CT images. AJR Am J Roentgenol. 2012;199(3):677–82. https://doi.org/10.2214/ajr.11.7999.
65. Asvadi NH, Arellano RS. Hydrodissection-assisted image-guided percutaneous biopsy of abdominal and pelvic lesions: experience with seven patients. AJR Am J Roentgenol. 2015;204(4):865–7. https://doi.org/10.2214/AJR.14.13040.
66. Kurup AN, Schmit GD, Morris JM, Atwell TD, et al. Avoiding complications in bone and soft tissue ablation. Cardiovasc Interv Radiol. 2017;40(2):166–76. https://doi.org/10.1007/s00270-016-1487-y.
67. Lee SJ, Choyke LT, Locklin JK, Wood BJ. Use of hydrodissection to prevent nerve and muscular damage during radiofrequency ablation of kidney tumors. J Vasc Interv Radiol. 2006;17(12):1967–9.
68. Khan F, Ho AM, Jamal JE, Gershbaum MD, et al. Long-term outcomes after percutaneous renal cryoablation performed with adjunctive techniques. Clin Imaging. 2017;12(50):62–7. https://doi.org/10.1016/j.clinimag.2017.12.003.
69. Kang TW, Rhim H, Lee MW, Kim YS, et al. Radiofrequency ablation for hepatocellular carcinoma abutting the diaphragm: comparison of effects of thermal protection and therapeutic efficacy. AJR Am J Roentgenol. 2011;196(4):907–13. https://doi.org/10.2214/AJR.10.4584.
70. Kang TW, Lee MW, Hye MJ, Song KD, et al. Percutaneous radiofrequency ablation of hepatic tumours: factors affecting technical failure of artificial ascites formation using an angiosheath. Clin Radiol. 2014;69(12):1249–58. https://doi.org/10.1016/j.crad.2014.07.012.
71. Kariya S, Tanigawa N, Kojima H, Komemushi A, et al. Radiofrequency ablation combined with CO_2 injection for treatment of retroperitoneal tumor: protecting surrounding organs against thermal injury. AJR Am J Roentgenol. 2005;185(4): 890–3.
72. Leroy JE, Le Péchon JC, Delafosse B, Fischler M. Is it necessary to revalue the risk of a gas embolism complicating an intervention with carbon dioxide insufflation? Ann Fr Anesth Reanim. 2007;26(5):459–63.
73. Buy X, Tok C-H, Szwarc D, et al. Thermal protection during percutaneous thermal ablation procedures: interest of carbon dioxide dissection and temperature monitoring. Cardiovasc Interv Radiol. 2009;32:529–34. https://doi.org/10.1007/s00270-009-9524-8.
74. Favelier S, Guiu S, Cherblanc V, Cercueil JP, et al. Transthoracic adrenal biopsy procedure using artificial carbon dioxide pneumothorax as outpatient procedure. Cardiovasc Interv Radiol. 2013;36(4):1184–7. https://doi.org/10.1007/s00270-012-0508-8 **Epub 2012 Nov 14**.
75. Garnon J, Cazzato RL, Koch G, Uri IF, et al. Trans-rectal ultrasound-guided autologous blood injection in the interprostatorectal space prior to percutaneous MRI-guided cryoablation of the prostate. Cardiovasc Interv Radiol. 2018;41(4):653–9. https://doi.org/10.1007/s00270-017-1853-4.
76. Majdalany BS, Willatt J, Chick JFB, Srinivasa RN, et al. Fibrillar collagen injection for organ protection during thermal ablation of hepatic malignancies. Diagn Interv Radiol. 2017;23(5):381–4. https://doi.org/10.5152/dir.2017.17120.
77. Hasegawa T, Takaki H, Miyagi H, Nakatsuka A, et al. Hyaluronic acid gel injection to prevent thermal injury of adjacent gastrointestinal tract during percutaneous liver radiofrequency ablation. Cardiovasc Interv Radiol. 2013;36(4):1144–6. https://doi.org/10.1007/s00270-013-0546-x.
78. Johnson A, Sprangers A, Cassidy P, Heyrman S, et al. Design and validation of a thermoreversible material for percutaneous tissue hydrodissection. J Biomed Mater Res B Appl Biomater. 2013;101(8):1400–9. https://doi.org/10.1002/jbm.b.32959.
79. Johnson A, Brace C. Heat transfer within hydrodissection fluids: An analysis of thermal conduction and convection using liquid and gel materials. Int J Hyperth. 2015;31(5):551–9. https://doi.org/10.3109/02656736.2015.1037799.
80. Zhang LL, Xia GM, Liu YJ, Dou R, et al. Effect of a poloxamer 407-based thermosensitive gel on minimization of thermal injury to diaphragm during microwave ablation of the liver. World J Gastroenterol. 2017;23(12):2141–8. https://doi.org/10.3748/wjg.v23.i12.2141.
81. Moreland AJ, Lubner MG, Ziemlewicz TJ, Kitchin DR, et al. Evaluation of a thermoprotective gel for hydrodissection during percutaneous microwave ablation: in vivo results. Cardiovasc Interv Radiol. 2015;38(3):722–30. https://doi.org/10.1007/s00270-014-1008-9.
82. Yamakado K, Nakatsuka A, Akeboshi M, Takeda K. Percutaneous radiofrequency ablation of liver neoplasms adjacent to the gastrointestinal tract after balloon catheter interposition. J Vasc Interv Radiol. 2003;14(9 Pt 1):1183–6.