MRI-Guided High-Dose-Rate Interstitial Brachytherapy of Hepatic Malignancies

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Introduction

Primary and secondary liver malignancies remain a major clinical challenge. Primary liver cancer is among the most common cancers worldwide and one of the leading causes of cancer-related mortality [1]. At the same time, the liver is a frequent site of metastatic spread, particularly in colorectal cancer, neuroendocrine tumors, breast cancer, and other gastrointestinal malignancies. As systemic therapies continue to improve, more patients present with limited hepatic tumor burden, oligometastatic disease, oligoprogression, or residual liver-dominant disease. In this setting, local treatment has become an increasingly important part of multidisciplinary oncologic care [2, 3].

Thermal ablation, including radiofrequency ablation and microwave ablation, is well established for small primary and secondary liver tumors. In appropriately selected patients, it offers low morbidity, short recovery times, and high rates of local tumor control. However, the physical principles of heat-based ablation define its limits. Tumors larger than 3 cm are more difficult to treat completely. Lesions adjacent to large vessels may be undertreated because of heat-sink effects. Tumors near the central bile ducts, gallbladder, stomach, duodenum, colon, heart, or diaphragm carry a higher risk of thermal injury to vulnerable structures. In these situations, a technically feasible needle position does not always translate into a safe and oncologically adequate ablation [4].

Interstitial high-dose-rate (HDR) brachytherapy offers an alternative way to think about local ablation [5–7]: Instead of heat, it uses radiation delivered from within the tumor. After percutaneous placement of one or more closed-ended applicator catheters, a high-activity Iridium-192 source is advanced by a robotic afterloader to predefined dwell positions. Based on three-dimensional treatment planning, a steep and conformal dose distribution can be generated around the catheter, with rapid dose fall-off outside the target volume. In clinical practice, single-session target doses typically range from 15 to 25 Gy, depending on tumor entity, target size, and adjacent organs at risk.

A growing body of clinical and dosimetric evidence supports the specific advantages of this approach [8–12]. First, it is not limited by heat-sink effects and can therefore be used close to major hepatic vessels. Second, because dose distribution can be calculated and adapted, it is particularly attractive for lesions adjacent to heat-sensitive structures. Third, large or irregular tumors can be treated by placing multiple catheters and shaping the dose distribution accordingly. Fourth, unlike many thermal ablations, catheter-based radiotherapy can often be performed under conscious sedation and local anesthesia rather than general anesthesia. Finally, in centers where HDR brachytherapy infrastructure is already established, the procedure can also be economically attractive, as disposable material costs are generally lower than those associated with many thermal ablation systems, and no dedicated ablation generator is required.

Patient selection remains essential. Candidates are typically discussed in an interdisciplinary tumor board that considers tumor entity, systemic disease status, liver function, coagulation parameters, previous biliary interventions, and alternative local or surgical options. Patients with impaired liver function, advanced cirrhosis, relevant coagulopathy, or biliary-enteric anastomoses require particular caution because of the increased risks of bleeding, infection, abscess formation, or hepatic decompensation [13]. A further practical limitation is organizational rather than technical: Successful liver HDR brachytherapy requires close collaboration between interventional radiology, radiation oncology, medical physics, and nursing staff. Without this infrastructure, the procedure cannot be implemented safely and reproducibly.

Advantages of MRI guidance

For many years, CT has been the workhorse modality for percutaneous catheter placement in interstitial liver brachytherapy. CT is fast, widely available, and provides reliable visualization of needles, sheaths, and catheters. However, CT guidance can be limited by poor soft-tissue contrast, particularly in small liver lesions or tumors located in complex anatomic regions such as the liver dome, caudate lobe, or central liver close to the hilum [14, 15].

MRI changes the interventional environment. Its superior soft-tissue contrast, combined with hepatocyte-specific contrast agents, can improve lesion conspicuity for a prolonged time window. This is highly relevant in the liver, where many small metastases or hepatocellular carcinomas are only faintly visible on CT or ultrasound but clearly delineated on hepatobiliary-phase MRI. In addition, MRI allows free selection of imaging planes, making it possible to align the slice orientation with the planned needle trajectory. With real-time gradient-echo MR fluoroscopy, the interventionalist can monitor needle advancement dynamically, including in oblique or double-oblique trajectories that would be difficult to appreciate with conventional axial CT fluoroscopy. Another advantage, of course, is that MRI guidance eliminates exposure to ionizing radiation for both patients and staff.

The value of MRI guidance is particularly evident when targeting small tumors or tumors at risk of geographic miss. A catheter placed slightly off-center may still allow target coverage by increasing the irradiated volume, but this comes at the cost of exposing more healthy liver parenchyma or nearby organs at risk. MRI-guided catheter placement aims to reduce this compromise: Better visualization enables more accurate central catheter positioning, which in turn may allow tighter dose distribution and better sparing of non-target tissue.

Our preliminary experience supports this concept. Between June 2023 and April 2024, a total of 27 patients with 54 liver lesions were treated in a prospective single-center trial investigating MRI-guided catheter-based radiotherapy for primary and secondary liver tumors. Procedures were performed under conscious sedation and local anesthesia on a 1.5T MRI system (MAGNETOM Sola Fit) equipped with a 15 cm loop coil.

The treated cohort included hepatocellular carcinoma, colorectal cancer metastases, gastrointestinal stromal tumor metastases, neuroendocrine tumor metastases, and metastases from other primaries. Median lesion diameter was 11 mm, highlighting the role of MRI guidance for small tumors. Compared with a propensity-score-matched CT-guided cohort from a large institutional control population, MRI-guided procedures required longer room time, with a median of 60 minutes, versus 46 minutes for CT guidance. However, MRI guidance was associated with a significantly lower non-target liver parenchyma irradiation (V5Gy: 15% vs. 43%), and preliminary 12-month local tumor control was higher in the MRI-guided cohort than in the matched CT-guided group (95.1% vs. 79.9%). Procedural complications were rare; one patient experienced minor bleeding that required neither transfusion nor intervention.

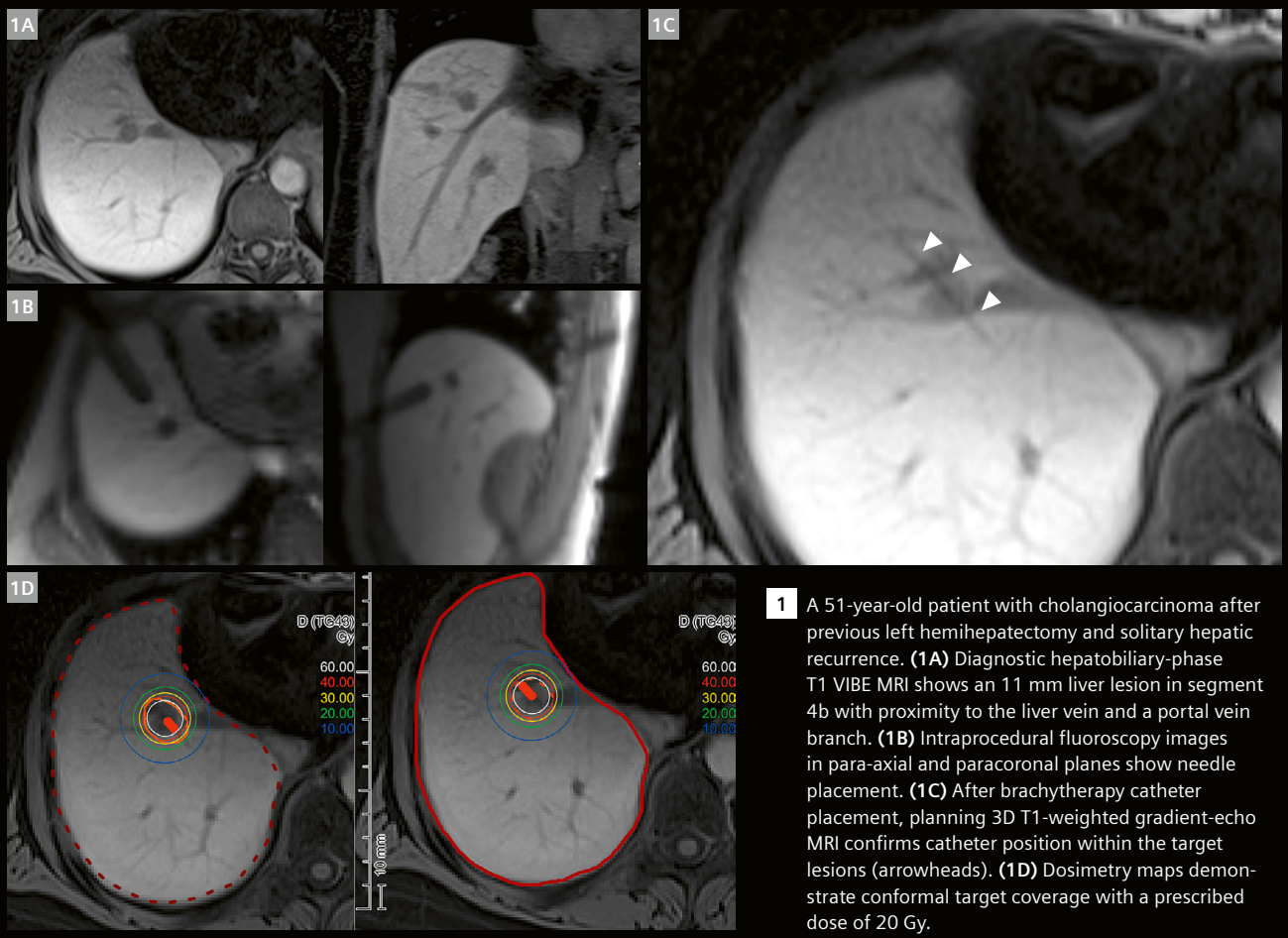
These early data suggest that the additional procedural time of MRI guidance may be offset by greater targeting confidence, reduced non-target irradiation, and potentially improved local tumor control. Further follow-up and larger cohorts will be needed, but for small or poorly CT-visible lesions, MRI-guided brachytherapy may represent a particularly promising direction.

HDR brachytherapy: How to do it

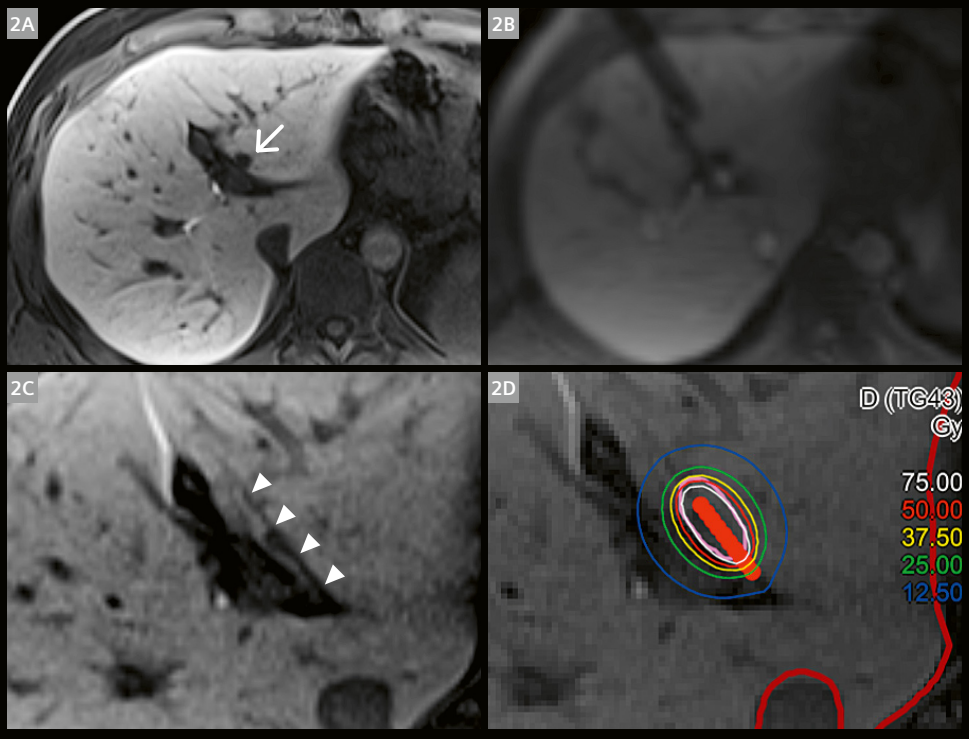
The workflow begins before the patient enters the interventional suite. Pre-procedural imaging is reviewed jointly by interventional radiology and radiation oncology. The number, size, and location of target lesions are assessed, as are the proximity of vessels, bile ducts, bowel, stomach, gallbladder, diaphragm, and heart. Laboratory evaluation includes coagulation parameters, platelet count, liver function tests, and renal function. Anticoagulation and antiplatelet therapy must be managed according to institutional and society recommendations. Patients with previous sphincterotomy, biliary stents, or biliary-enteric anastomoses should receive appropriate antibiotic prophylaxis because of the increased risk of abscess formation after liver interventions.

Most procedures can be performed under conscious sedation and local anesthesia. Oxygen supplementation, ECG monitoring, pulse oximetry, and repeated blood pressure measurements are mandatory. Sedation is typically achieved with titrated opioid and benzodiazepine administration, while preserving spontaneous breathing. Reversal agents and airway support must be immediately available, and the team must be familiar with sedation-related emergencies.

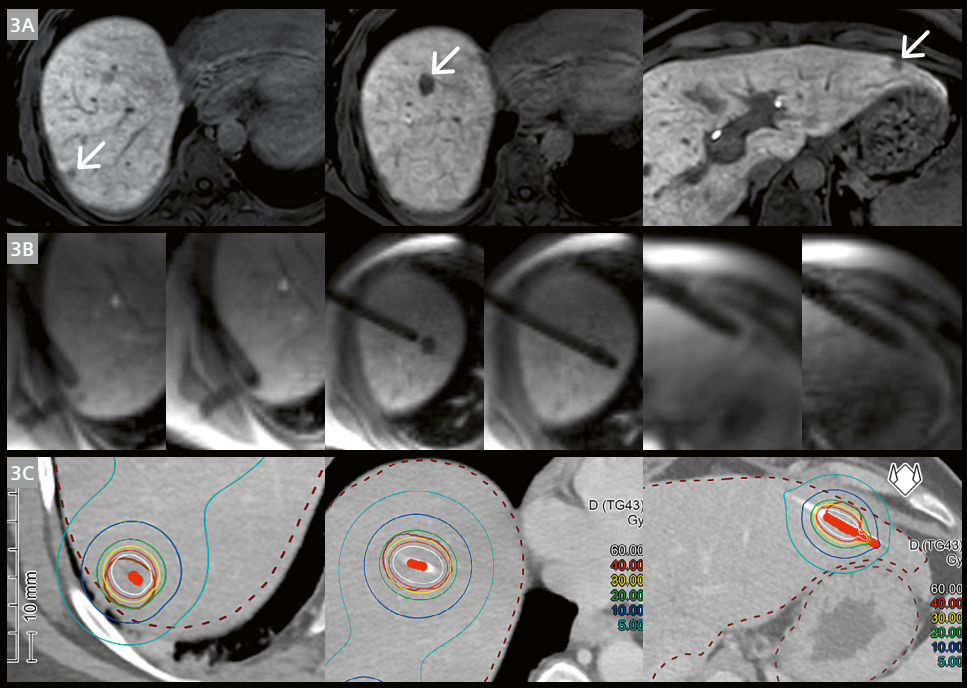
In MRI-guided procedures, the patient is positioned on the scanner table 15 minutes after the administration of gadoxetic acid (0.1 mmol/kg body weight). Axial and coronal hepatobiliary-phase T1-weighted images are acquired for lesion localization and access planning. After sterile preparation, local anesthetic is infiltrated into the skin, subcutaneous tissues, and liver capsule. The puncture is then performed with an 18G coaxial needle under



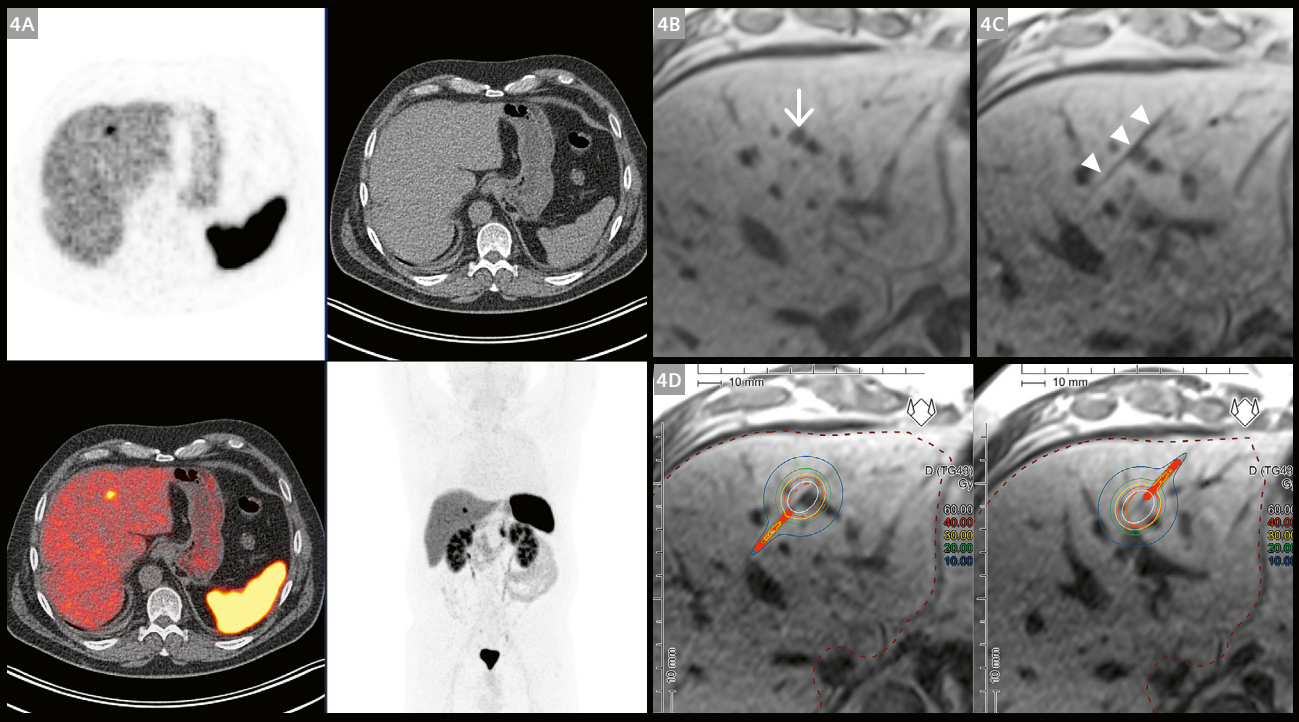
1 A 51-year-old patient with cholangiocarcinoma after previous left hemihepatectomy and solitary hepatic recurrence. **(1A)** Diagnostic hepatobiliary-phase T1 VIBE MRI shows an 11 mm liver lesion in segment 4b with proximity to the liver vein and a portal vein branch. **(1B)** Intraprocedural fluoroscopy images in para-axial and paracoronal planes show needle placement. **(1C)** After brachytherapy catheter placement, planning 3D T1-weighted gradient-echo MRI confirms catheter position within the target lesions (arrowheads). **(1D)** Dosimetry maps demonstrate conformal target coverage with a prescribed dose of 20 Gy.



2 A 45-year-old patient with solitary colorectal liver metastasis. **(2A)** Diagnostic hepatobiliary-phase T1 VIBE MRI shows an 8 mm liver lesion in segment 2, directly adjacent to the left portal vein (arrow). **(2B)** Intraprocedural fluoroscopy image shows needle placement. **(2C)** After brachytherapy catheter placement, planning 3D T1-weighted gradient-echo MRI confirms catheter position within the target lesions (arrowheads). **(2D)** Dosimetry map demonstrates conformal target coverage with a prescribed dose of 25 Gy.



3 A 55-year-old patient with oligometastatic breast cancer (three liver metastases). **(3A)** Diagnostic hepatobiliary-phase T1 VIBE MRI shows three small liver lesions: one in segment 7 measuring 6 mm (left), one in segment 8 measuring 18 mm (middle), and one in segment 3 measuring 7 mm (right). **(3B)** Intraprocedural fluoroscopy images show needle placement in para-axial plane. **(3C)** After brachytherapy catheter placement, planning with contrast-enhanced CT was required for treatment planning as the catheter-tip conspicuity was insufficient in MRI. Dosimetry maps demonstrate conformal target coverage with a prescribed dose of 20 Gy.



4 A 57-year-old patient with a history of bronchial neuroendocrine tumor and hepatic recurrence following 10 years of remission. **(4A)** 68Ga-DOTATATE PET/CT shows a solitary hepatic metastasis with enhanced uptake. **(4B)** Hepatobiliary-phase T1 VIBE MRI shows a 7 mm liver lesion in segment 4a with proximity to a portal vein branch. **(4C)** After brachytherapy catheter placement, planning 3D T1-weighted gradient-echo MRI confirms decent catheter position (arrowheads). **(4D)** Dosimetry maps demonstrate conformal target coverage with a prescribed dose of 20 Gy.

real-time gradient-echo MR fluoroscopy (TE 3.4 ms, TR 7.3 ms, FA 30°). Once optimal needle positioning is confirmed, the inner stylet is withdrawn and a stiff 0.035-inch guidewire is introduced in retrograde orientation (rear-end first) to enable exchange of the needle for a 6 French/25 cm sheath with dilator using the Seldinger technique. After removal of the wire and dilator, a closed-ended 6F brachytherapy catheter is advanced through the sheath, and its extracorporeal length is measured and marked to detect potential displacement. The catheter is fixed carefully at the skin.

For larger tumors or irregular target volumes, multiple catheters may be required. Their number and geometry are determined by the expected dose distribution and the relationship of the lesion to surrounding organs at risk. After catheter placement, a three-dimensional gradient-echo MRI sequence is used for immediate position verification, although contrast-enhanced CT might be required for treatment planning and dosimetric calculations if catheter-tip conspicuity is insufficient. The target volume and organs at risk are segmented by the radiation oncology team, and the medical physicist calculates a plan based on catheter position, dwell points, and dwell times. If coverage is insufficient, an additional catheter can be placed before treatment delivery.

The patient is then connected to the HDR afterloader. The Iridium-192 source travels through the catheter to the programmed dwell positions, delivering the prescribed dose from inside the tumor. Treatment times vary according to source strength, dose prescription, tumor volume, and number of catheters, but usually remain clinically practical within a single session. Depending on tumor entity, commonly prescribed target doses are 15 Gy for hepatocellular carcinoma (HCC), 25 Gy for metastatic colorectal cancer, and 20 Gy for other tumor entities. The catheter tract is routinely irradiated with 5 Gy before removal to reduce the risk of tumor cell seeding.

After treatment, catheters are removed under careful hemostatic technique. The access tract is sealed with gelatin sponge pledgets during sheath withdrawal to reduce bleeding risk. Post-procedural monitoring includes clinical observation and ultrasound to exclude hematoma, subcapsular bleeding, or free intra-abdominal fluid. Most patients can be managed without intensive post-procedural care, although monitoring must be adapted to liver function, coagulation status, sedation depth, and comorbidities.

Complications are uncommon but must be anticipated. The most relevant are bleeding, infection or abscess, transient pain, nausea, and rare bile-duct injury or hepatic decompensation. The risk profile depends on tumor burden, access route, liver function, coagulation status, and biliary anatomy.

Follow-up imaging requires familiarity with post-radiation changes. The treatment zone may initially appear larger than the original tumor and can show edema, peripheral arterial hyperenhancement, or delayed parenchymal enhancement. These findings should not be mistaken for viable tumor unless there is new or increasing nodular enhancement suggestive of local progression. MRI is particularly valuable for follow-up after liver-directed therapy because it combines high soft-tissue contrast with multiphasic and hepatobiliary information.

Representative case examples are shown in Figures 1–4.

Conclusion

MRI-guided interstitial HDR brachytherapy brings together two strengths: the precision of modern interventional MRI and the conformal dose delivery of catheter-based radiotherapy. For hepatic malignancies that are small, poorly visible on CT, close to vessels, adjacent to heat-sensitive structures, or unsuitable for thermal ablation, this technique expands the local treatment armamentarium beyond heat.

CT guidance will remain important because of its speed, availability, and robustness. However, MRI guidance offers a compelling advantage in selected patients: improved lesion visibility, flexible imaging planes, real-time needle guidance without ionizing radiation to the operator, and the potential for more precise catheter placement. Preliminary single-center data indicate that MRI-guided catheter-based radiotherapy is feasible and safe, with low complication rates, reduced non-target liver irradiation, and encouraging early local control.

The future of liver-directed therapy will likely be increasingly individualized. Some lesions are best treated surgically, others thermally, transarterially, stereotactically, or systemically. MRI-guided HDR brachytherapy occupies a distinct and valuable niche within this spectrum. Its broader adoption will depend not only on technology, but also on interdisciplinary workflows that unite interventional radiology, radiation oncology, medical physics, and patient-centered oncologic decision-making.

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