Section: Miscellaneous

Original Research Article

IMAGE-GUIDED CO-ABLATION OF PRIMARY HEPATIC TUMORS USING A LIQUID NITROGEN–BASED CRYOTHERMAL SYSTEM: TECHNICAL PERFORMANCE, PROCEDURAL CHARACTERISTICS, AND EARLY CLINICAL OUTCOMES — A SINGLE-CENTRE OBSERVATIONAL CASE SERIES

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ABSTRACT

Background: Percutaneous ablation is now an established, minimally invasive alternative to surgical resection for selected patients with primary hepatic malignancies. Co-ablation is a cryogenic technique that uses liquid nitrogen to freeze tissue and circulating alcohol to actively thaw it within a closed-loop probe, enabling precise, repeatable ice-ball formation and freeze–thaw cycling that may maximize tumor necrosis while sparing the surrounding liver. The aim is to evaluate the technical feasibility, procedural characteristics, and early safety of image-guided percutaneous co-ablation in patients with primary hepatic tumors treated at a single tertiary referral centre.

Materials and Methods: In this single-centre, retrospective, observational case series, 18 consecutive ablation sessions were performed in 17 patients with primary hepatic tumours between August 26, 2025, and January 29, 2026, using the Hygea Coalition AI Epic Series system (RAL26 and RBL20 probe configurations) under CT and/or ultrasound guidance. Technical success required complete intra-procedural tumor coverage with an adequate ablative margin on real-time imaging. Demographic, tutor, procedural, and safety data were analysed descriptively.

Results: All 18 sessions (11 men [61.1%], 7 women [38.9%]) were completed as planned, a technical success rate of 100%. Tumor size ranged from 1.5 to 4.5 cm (mean 3.03 ± 0.81 cm; median 3.0 cm). Procedures lasted 60–90 minutes (mean 74.1 minutes). A single probe was sufficient in 16 of 18 sessions (88.9%); two probes were used in the two sessions involving tumour's ≥4 cm. RAL26 was used in 7 sessions (38.9%) and RBL20 in 11 (61.1%). Freeze–thaw cycles ranged from 2 to 5 (mean 2.67 ± 0.97), with a mean maximum freeze time of 12.5 ± 4.8 minutes per cycle. No major complications (Society of Interventional Radiology [SIR] grade C–F) occurred; minor events, where present, were self-limiting. Early follow-up imaging in the available cases showed non-enhancing ablation zones without evidence of residual viable tumor.

Conclusion: Image-guided co-ablation using the HygeaCoablation AI Epic Series liquid nitrogen–alcohol cryothermal system is technically feasible and safe across a clinically relevant range of tumor sizes. Prospective multicentre trials with standardized oncologic follow-up are needed to confirm long-term efficacy.

Keywords: hepatic tumor ablation; co-ablation; cryoablation; liquid nitrogen; image-guided intervention; interventional oncology; hepatocellular carcinoma; minimally invasive locoregional therapy.

INTRODUCTION

Primary hepatic tumors — chiefly hepatocellular carcinoma (HCC) and intrahepatic cholangiocarcinoma — represent a large and growing global cancer burden. HCC alone is the sixth most common malignancy worldwide and the third leading cause of cancer death, with roughly 906,000 new cases and 830,000 deaths recorded in 2020.[1] Its incidence tracks closely with chronic liver disease, cirrhosis, hepatitis B and C infection, and metabolic-associated fatty liver disease. Despite advances in systemic therapy, including checkpoint inhibitors and targeted agents, most patients still present with intermediate or advanced disease, which limits eligibility for curative resection or transplantation.[2].

For patients with early-stage disease who cannot or choose not to undergo surgery, minimally invasive ablation has become a well-accepted alternative. Radiofrequency ablation (RFA) and microwave ablation (MWA) are the most extensively studied thermal options, achieving local control above 85–95% for tumors ≤3 cm.[3,4] Both, however, are limited by the heat-sink effect near vessels, impedance-related failure of energy delivery, and an ablation zone that cannot be directly visualized during treatment. Cryoablation avoids several of these problems: the resulting ice-ball is directly visible on ultrasound and CT, allowing real-time confirmation of margin adequacy rather than reliance on a temperature-based surrogate.[5].

Cryoablation destroys tumor cells through a well-described cascade — rapid freezing, intracellular ice formation, osmotic dehydration, membrane rupture, vascular stasis, and coagulative or apoptotic necrosis during thaw.[6] Newer liquid nitrogen–based systems reach probe-tip temperatures as low as −196°C, well below the roughly −185°C achievable with argon-helium platforms.[7] producing faster and more uniform ice-ball growth.

Co-ablation extends this principle further: a closed-loop probe delivers liquid nitrogen for freezing and circulates alcohol for active thawing, rather than the passive or helium-mediated thawing used in older systems. This dual-agent design allows the operator to control freeze–thaw cycling directly, potentially increasing the cellular injury achieved per cycle while shortening overall procedure time. The HygeaCoablation AI Epic Series is one such platform, offering two probe configurations — RAL26 and RBL20 — that differ in ablation-zone geometry and optimal tumor size range.[8].

Image guidance is central to safe percutaneous ablation: CT offers superior spatial resolution for planning probe trajectory and assessing depth, while ultrasound provides real-time, radiation-free monitoring of ice-ball growth.[9,10. On ultrasound, the advancing ice front produces a sharp acoustic shadow; on CT it appears as a hypodense zone with a characteristic “donut sign,” both of which help confirm margins during the procedure.[11].

Despite these theoretical advantages, peer-reviewed clinical data specific to the Hygea system remain scarce, as most cryoablation literature concerns argon-based devices. We report our early experience with image-guided co-ablation using this system in 18 consecutive sessions for primary hepatic tumors at a single tertiary center over six months, describing technical feasibility, procedural characteristics, probe selection, and early safety outcomes.

MATERIALS AND METHODS

Study Design: This single-centre, retrospective, observational case series was conducted at a tertiary academic centre with an established interventional oncology program. All procedures were performed within standard clinical care between August 26, 2025, and January 29, 2026, in accordance with the Declaration of Helsinki (2013 revision). Institutional review board approval was waived given the retrospective, observational design, and all patient data were de-identified before analysis.

Patient Selection: Consecutive patients with a radiologically or histologically confirmed primary hepatic tumor who underwent co-ablation during the study period were included; selection was made by the institution's multidisciplinary tumor board (hepatology, oncology, surgery, and interventional radiology).

Inclusion criteria

A confirmed primary hepatic tumor on cross-sectional imaging or biopsy; a lesion amenable to percutaneous ablation (generally ≤5 cm) without critical anatomical proximity; Child-Pugh class A or B hepatic reserve; ECOG performance status ≤2; and no systemic metastatic disease outside a tumor board–approved oligometastatic management plan.

Exclusion criteria

Uncorrectable coagulopathy (INR >1.8 or platelets <50 × 10⁹/L); tumor contiguity with major bile ducts, central hepatic vasculature, or bowel precluding safe probe placement; active systemic infection; contraindication to sedation or anaesthesia; or inability to provide informed consent.

Pre-Procedural Imaging: All patients underwent contrast-enhanced CT of the abdomen (non-contrast, arterial, portal venous, and delayed phases) and/or hepatic ultrasound within four weeks before ablation. Tumor size, morphology, enhancement pattern, and relationship to hepatic vasculature were

documented, and the operator prospectively assessed ultrasound conspicuity to select the intra-procedural guidance modality.

Co-Ablation Device: The HygeaCoablation AI Epic Series (Hygea Medical Technologies) is a closed-loop cryothermal platform that uses liquid nitrogen as the freezing agent (probe tip ≤−196°C) and intraluminal alcohol circulation as the active thawing medium. Two probes were used: the RAL26, providing a larger ablation zone for tumors >3 cm, and the RBL20, the standard configuration for tumors ≤3 cm. Probe choice was made by the operator based on lesion size and geometry.

Procedural Technique: Procedures were performed in the interventional radiology suite under sterile technique with standard cardiorespiratory monitoring. After local anaesthesia (1% lidocaine, 5–10 mL) and conscious sedation (intravenous midazolam and fentanyl) or general anaesthesia where clinically indicated, the probe was advanced percutaneously under real-time ultrasound and/or CT fluoroscopic guidance to the centre of the target lesion, with position adjusted as needed for irregular or bilobar tumor geometry.

Each session comprised sequential freeze–thaw cycles. During the freeze phase, liquid nitrogen circulation drove progressive ice-ball formation, monitored in real time as an expanding acoustic shadow on ultrasound or a hypodense zone on CT; freeze duration ranged from 5 to 20 minutes per cycle depending on tumor size and intra-procedural assessment. Alcohol circulation then actively thawed the tissue over approximately 1–3 minutes per cycle. The number of cycles was determined by the operator based on lesion characteristics and intra-procedural confirmation of ablation adequacy. For tumors ≥4 cm, two probes were placed with spacing designed for confluent ice-ball overlap, with cycles delivered sequentially or simultaneously per operator preference.

Technical Success and Outcome Definitions:

Technical success: complete intra-procedural coverage of the tumor by the ablation ice-ball, with a circumferential margin ≥5 mm beyond the perceived tumor boundary, without a major complication precluding procedure completion.

Technical failure: inability to complete the planned ablation protocol because of device malfunction, loss of adequate probe placement, or termination due to a complication.

Early local tumor progression (where follow-up imaging was available): new or residual arterially enhancing tissue at or adjacent to the ablation zone, per modified RECIST (mRECIST) criteria for HCC.[12].

Complication Classification: Adverse events were prospectively classified using the Society of Interventional Radiology (SIR) system: grade A–B events (minor, requiring no or nominal therapy) as minor complications, and grade C–F events (requiring therapy, unplanned hospitalization, permanent sequelae, or death) as major complications.[13]

Statistical Analysis: Descriptive analysis was performed using Python 3.12 (pandas, NumPy). Normally distributed continuous variables are reported as mean ± standard deviation (SD) with range; non-normally distributed variables are additionally reported as median with interquartile range (IQR). Categorical variables are expressed as counts and percentages. No inferential statistics were performed, consistent with the observational design and absence of a comparator arm; missing data are reported explicitly and excluded from the relevant denominators.

RESULTS

Patient Demographics and Tumor Characteristics: Eighteen ablation sessions were performed in 17 patients (one patient was treated twice) over the six-month study period, comprising 11 men (61.1%) and 7 women (38.9%); all treated lesions were hepatic [Table 1]. Maximum axial tumor dimension ranged from 1.5 to 4.5 cm (mean 3.03 ± 0.81 cm; median 3.0 cm), distributed as ≤2.0 cm in 3 sessions (16.7%), >2.0–3.0 cm in 8 (44.4%), >3.0–4.0 cm in 6 (33.3%), and >4.0 cm in 1 (5.6%) (Table 5). Several lesions had biaxial measurements up to 3.5 × 3.4 cm [Table 2], and no tumor showed extrahepatic extension.

Procedural Characteristics: Procedure duration, recorded in 17 of 18 sessions, was 60 minutes in 9 (52.9%) and 90 minutes in 8 (47.1%), for a mean of 74.1 minutes. A single probe was sufficient in 16 sessions (88.9%); two probes were required in the two sessions involving tumors ≥4 cm (4.0 cm and 4.5 cm), both using the RBL20 configuration, with intra-procedural repositioning performed in one to optimize coverage. The RAL26 probe was selected in 7 sessions (38.9%), predominantly for tumors >3 cm, and the RBL20 in 11 sessions (61.1%), predominantly for tumors ≤3 cm. Freeze–thaw cycles ranged from 2 to 5 (mean 2.67 ± 0.97; median 2), most often 2 cycles (61.1% of sessions). Maximum freeze time per cycle, documented in 12 sessions, ranged from 5 to 20 minutes (mean 12.5 ± 4.8 minutes), with active thaw lasting approximately 1–3 minutes throughout [Table 3].

Technical Success and Safety: Technical success — complete ice-ball coverage of the tumor with an adequate margin on real-time imaging — was achieved in all 18 sessions (100%). In the one session requiring repositioning, subsequent cycles achieved confluent coverage and technical success was confirmed. No major complications (SIR grade C–F), including hemorrhage, biliary or vascular injury, cryoshock, or 30-day mortality, occurred in any session; minor events, where they occurred, were self-limiting and managed conservatively [Table 4].

Early Follow-Up Imaging: Where early follow-up imaging was available, contrast-enhanced CT or MRI showed well-demarcated, non-enhancing ablation zones with a thin rim of perilesional inflammatory change, without arterially enhancing nodularity to suggest residual viable tumor [Table 5].

Table 1: Patient Demographics and Clinical Characteristics (N = 18 Sessions, 17 Patients)

Characteristic	n (%)	Details / Range
Total ablation sessions	18	Study period: Aug 2025–Jan 2026
Total patients treated	17	One patient underwent 2 sessions
Sex — Male	11 (61.1%)	—
Sex — Female	7 (38.9%)	—
Target organ	Liver — 18 (100%)	All hepatic
Tumor size — mean ± SD	3.03 ± 0.81 cm	Range: 1.5–4.5 cm
Tumor size — median (IQR)	3.0 cm	IQR: 2.5–3.5 cm
Study period	Aug 26, 2025 – Jan 29, 2026	~6 months

Table 2: Individual Session Data — Anonymized (N = 18 Sessions)

Session No.	Date	Sex	Tumor Size (cm)	Duration (min)	Probe Model	No. of Probes	F–T Cycles	Max Freeze Time/Cycle
1	26 Aug 2025	M	4.0	60	RBL20	1	2	8 min
2	13 Oct 2025	F	4.0	60	RAL26	1	2	8 min
3	14 Oct 2025	M	3.0 × 2.7	60	RAL26	1	2	10 min
4	16 Oct 2025	M	2.5	60	RBL20	1	2	5 min
5	17 Oct 2025	M	4.0	90	RBL20	2	5	NR
6	21 Oct 2025	M	2.7	60	RBL20	1	2	NR
7	22 Oct 2025	M	3.0	60	RBL20	1	2	NR
8	05 Nov 2025	F	3.0 × 3.0	90	RAL26	1	2	10 min
9	05 Nov 2025	F	2.3 × 1.2	NR	RBL20	1	2	15 min
10	17 Nov 2025	F	2.5 × 2.7	60	RBL20	1	2	12 min
11	18 Nov 2025	F	4.5	90	RBL20	2	3	12 min
12	25 Nov 2025	F	2.0	60	RBL20	1	3	10 min
13	03 Dec 2025	M	3.0	60	RAL26	1	2	20 min
14	04 Dec 2025	M	3.4	90	RAL26	1	2	15 min
15	27 Dec 2025	M	3.5	90	RAL26	1	4	18 min
16	22 Jan 2026	M	1.5	90	RBL20	1	4	20 min
17	28 Jan 2026	M	2.0	90	RBL20	1	3	NR
18	29 Jan 2026	F	3.5 × 3.4	90	RAL26	1	4	NR
Summary	Aug 2025–Jan 2026	M:11 F:7	Mean 3.03±0.81, range 1.5–4.5	Mean 74.1 (60:9, 90:8)	RAL26:7 RBL20:11	1 probe:16 2 probes:2	Mean 2.67±0.97, range 2–5	Mean 12.5±4.8, range 5–20

F–T = freeze–thaw; NR = not recorded; M = male; F = female. Sessions 5 and 11 required dual-probe configurations.

Table 3: Summary of Procedural Characteristics (N = 18 Sessions)

Parameter	n (%) or Value	Details / Range
Procedure Duration		
60 minutes	9 (52.9%) *	—
90 minutes	8 (47.1%) *	—
Not recorded	1 (5.6%)	—
Mean duration	74.1 minutes	Range: 60–90 min
Probe Configuration		
Single probe	16 (88.9%)	—
Dual probe	2 (11.1%)	Tumors ≥4 cm
RAL26 (sessions)	7 (38.9%)	Tumors >3 cm
RBL20 (sessions)	11 (61.1%)	Tumors ≤3 cm (typical)
Freeze–Thaw Cycles		
Mean ± SD	2.67 ± 0.97	—
Median (IQR)	2 (2–3)	—
Range	2–5 cycles	—
2 cycles	11 (61.1%)	—
3 cycles	3 (16.7%)	—
4 cycles	3 (16.7%)	—
5 cycles	1 (5.6%)	—
Freeze Time per Cycle (n = 12)		
Mean ± SD	12.5 ± 4.8 min	—
Range	5–20 min	—
Active thaw duration / cycle	~1–3 minutes	Operator-controlled
Technical success rate	18/18 (100%)	—

* Percentages based on 17 sessions with documented duration (1 session not recorded).

Table 4: Peri-Procedural Safety Outcomes (N = 18 Sessions)

Adverse Event / Outcome	n (%)	SIR Grade
Major complications (Grade C–F)	0 (0%)	—
Haemorrhage / hematoma	0 (0%)	—
Biliary injury / biloma	0 (0%)	—
Vascular injury	0 (0%)	—
Cryoshock	0 (0%)	—
Pneumothorax / pleural injury	0 (0%)	—
Tumor seeding along probe tract	0 (0%)	—
Procedure-related 30-day mortality	0 (0%)	—
Minor complications (Grade A–B)	Not systematically graded	A–B
All sessions completed as planned	18/18 (100%)	—

SIR = Society of Interventional Radiology adverse event classification.

Table 5. Tumor Size Distribution by Maximum Axial Dimension (N = 18 Sessions)

Size Category	Sessions n (%)	Probe Configuration
≤2.0 cm	3 (16.7%)	RBL20 × 1
>2.0–3.0 cm	8 (44.4%)	RBL20 × 1
>3.0–4.0 cm	6 (33.3%)	RAL26 × 1 or RBL20 × 1
>4.0 cm	1 (5.6%)	RBL20 × 2
Total	18 (100%)	—

4. Imaging Findings:

4.1 Pre-Ablation Tumor Characterization:

On pre-procedural contrast-enhanced CT, lesions showed imaging features typical of primary hepatic malignancy, most often arterial hyperenhancement with portal-venous washout consistent with HCC by LI-RADS/AASLD criteria, or, in ICC-type lesions, progressive peripheral enhancement. Tumor margins ranged from well-defined to irregular, and the relationship of each lesion to major vasculature and bile ducts was assessed to plan probe trajectory.

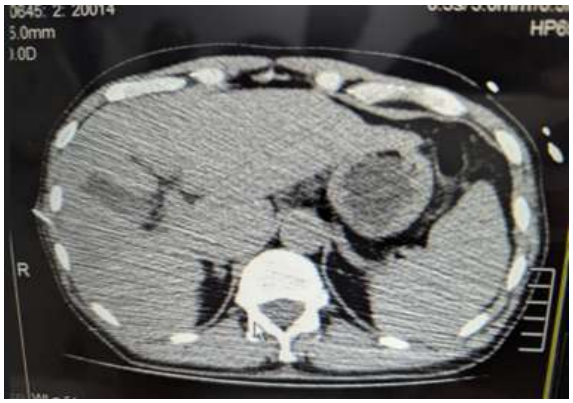


Figure 1A: Pre-Procedure Imaging — Case 1

Axial arterial-phase contrast-enhanced CT showing a hyper vascular hepatic lesion (arrow) with arterial hyperenhancement and portal-venous washout, consistent with a primary hepatic tumor. Callipers mark the maximum axial and orthogonal dimensions. The lesion's relationship to adjacent hepatic vasculature was assessed before the procedure, and pre-procedural imaging confirmed suitability for percutaneous co-ablation.

4.2 Intra-Procedural Ice-Ball Monitoring

During the freeze phase, a well-demarcated cryoablation zone developed around the probe tip — visible on ultrasound as an expanding hyperechoic arc with posterior acoustic shadowing, and on CT as a sharply marginated hypodense volume. Probe position within the lesion was confirmed on axial and reformatted images before the first freeze cycle in every case.

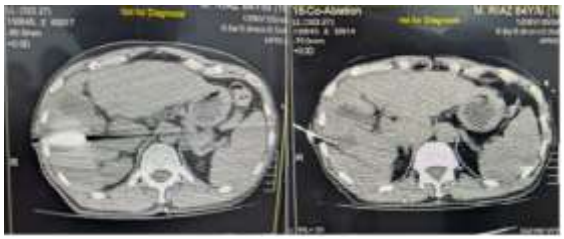


Figure 1B: Intra-Procedural Imaging — Case 1

Intra-procedural CT and ultrasound images showing the co-ablation probe tip (arrowhead) positioned centrally within the target lesion, with a hypodense ice-ball (dashed margin) expanding to encompass the tumor with an adequate circumferential margin. A single RBL20 probe was used; the probe track is seen as a linear hypodense artifact extending from the skin entry site to the lesion, without involvement of adjacent vascular or biliary structures.

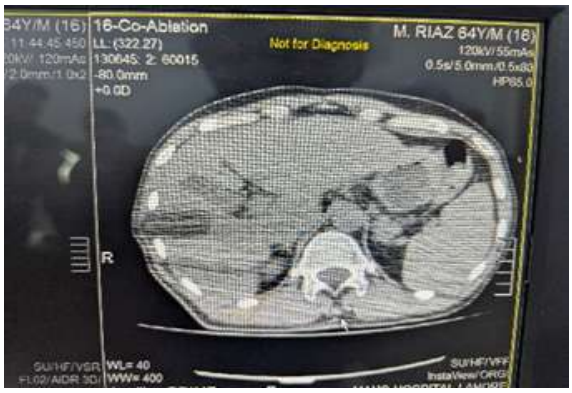


Figure 1C: Immediate Post-Procedure Imaging — Case 1

Immediate Post-Procedural Ablation Zone: Immediately after ablation, each treatment site showed a well-circumscribed, heterogeneous, predominantly hypodense cavity bordered by a thin rim of perilesional edema. On contrast-enhanced sequences obtained immediately post-procedure, no residual arterial enhancement was seen within or at the margin of the ablation zone, and the ablation volume consistently exceeded the original tumor dimensions, confirming an adequate margin.

Axial CT obtained immediately after co-ablation showing a well-circumscribed, heterogeneous hypodense ablation cavity (dashed outline) exceeding the pre-procedural tumor dimensions, confirming an adequate margin. A thin rim of perilesional edema and inflammatory change (arrowhead) is a normal post-ablation finding; no residual arterially enhancing tissue is seen within or at the margin of the cavity.

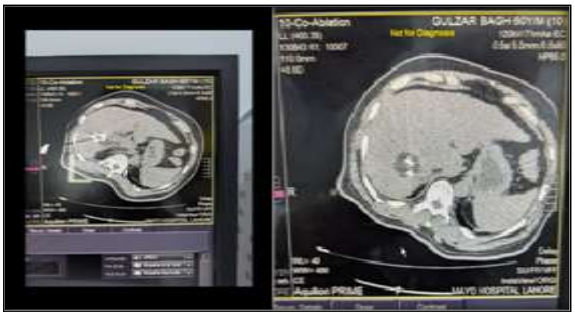
Early Follow-Up Imaging Response: On early follow-up imaging, the ablation cavity progressively organized, decreasing in volume and becoming a well-defined, non-enhancing cavity consistent with coagulative necrosis and early fibrotic change. No arterially enhancing nodularity, peripheral washout, or new satellite lesion was seen in the evaluated cases, indicating an absence of early radiological evidence of residual or recurrent tumor.

[Figure 1D] Follow-Up Imaging — Case 1

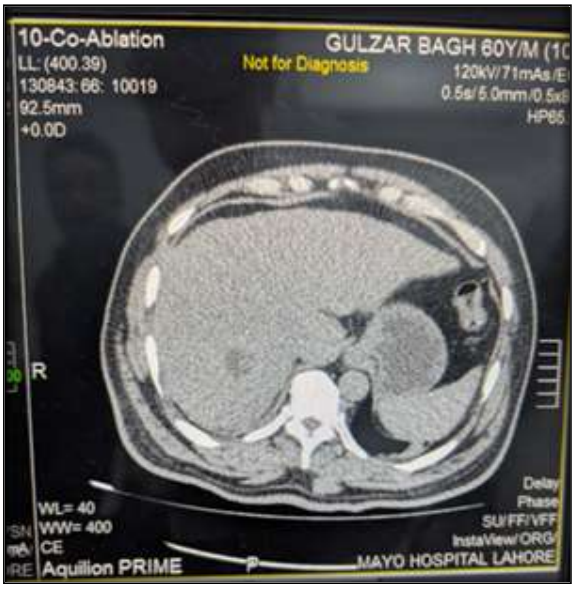
Axial contrast-enhanced CT obtained at early follow-up after co-ablation of the hepatic lesion, showing a well-defined, non-enhancing hypodense cavity consistent with evolving coagulative necrosis and early fibrotic organization. Comparison with the immediate post-procedural imaging shows a decrease in ablation zone volume and progressive boundary definition, with no arterially enhancing nodularity or new satellite lesion — findings consistent with a complete early treatment response.

Case 2: Pre-Procedure Imaging

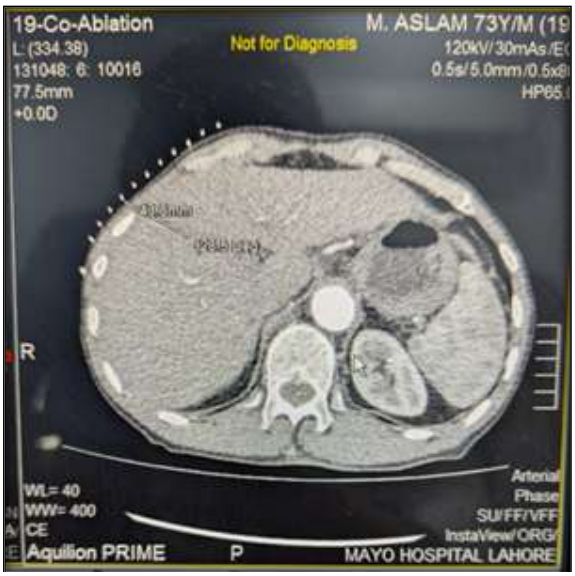
Intra-Procedural Ice-Ball Monitoring



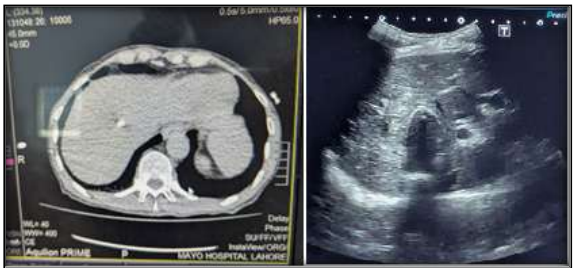
Immediate Post-Procedural Ablation Zone



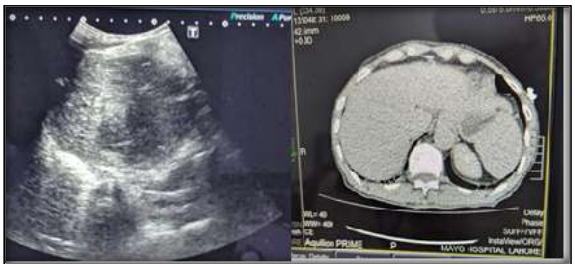
Case 3: Pre-Procedure Imaging



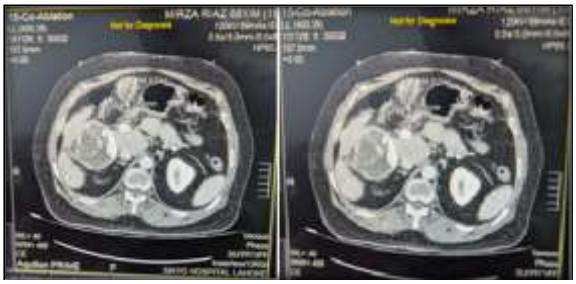
Intra-Procedural Ice-Ball Monitoring



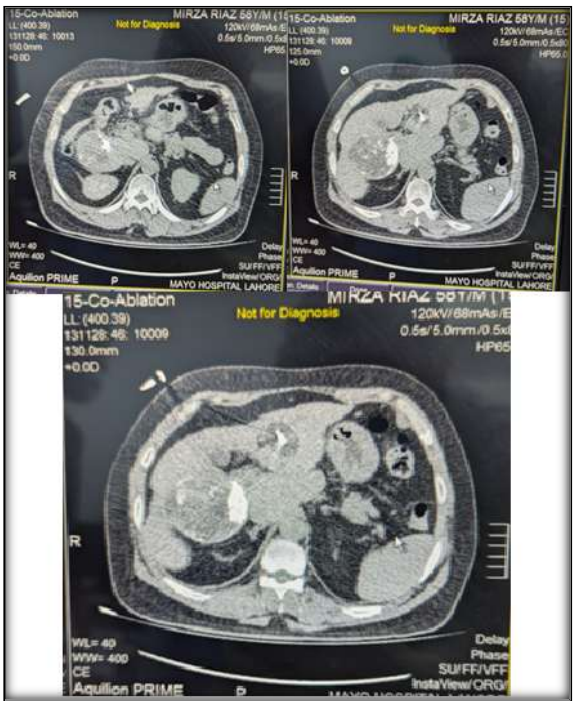
Immediate Post-Procedural Ablation Zone



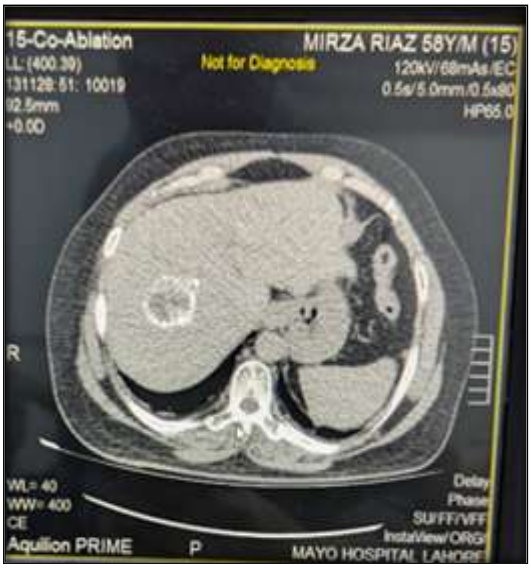
Case 4: Pre-Procedure Imaging



Intra-Procedural Ice-Ball Monitoring



Immediate Post-Procedural Ablation Zone



Statistical Figures

[Figures 2A–2F] summarize the key procedural and outcome statistics across all 18 co-ablation sessions, complementing the tabular data in Section 3 and [Tables 1–5].

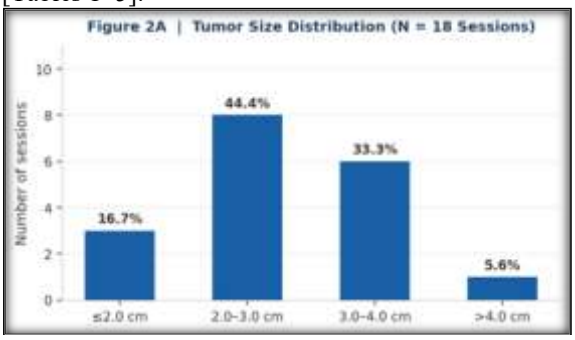


Figure 2A: Tumor Size Distribution

Distribution of treated lesions by maximum axial tumor dimension (N = 18 sessions). Most sessions involved tumors in the 2.0–3.0 cm range (44.4%), followed by 3.0–4.0 cm (33.3%), ≤2.0 cm (16.7%), and >4.0 cm (5.6%), reflecting a clinically representative size spectrum.

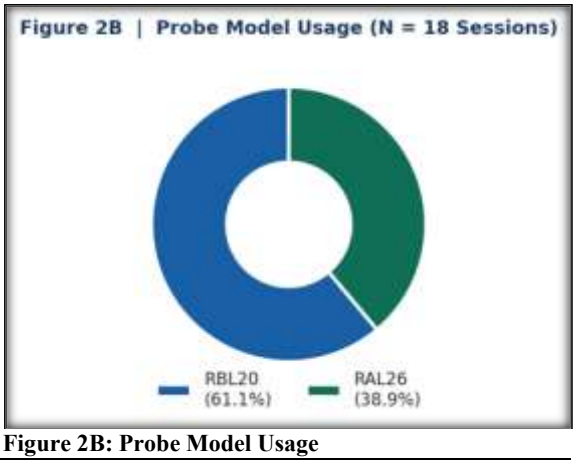


Figure 2B: Probe Model Usage

Distribution of probe configurations across all 18 sessions. RBL20 was used in 11 sessions (61.1%),

mainly for tumors ≤3 cm, while RAL26 was selected in 7 sessions (38.9%) for larger lesions.

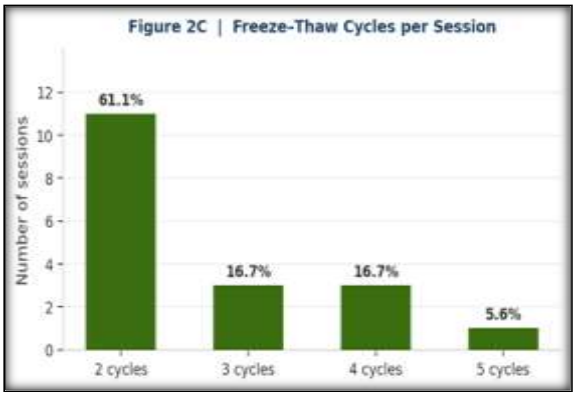


Figure 2C: Freeze–Thaw Cycles per Session

Frequency distribution of freeze–thaw cycle counts across all 18 sessions. Most sessions (61.1%) used 2 cycles; sessions with 3, 4, or 5 cycles reflect operator-directed adjustments for larger or geometrically complex lesions (mean 2.67 ± 0.97 cycles).

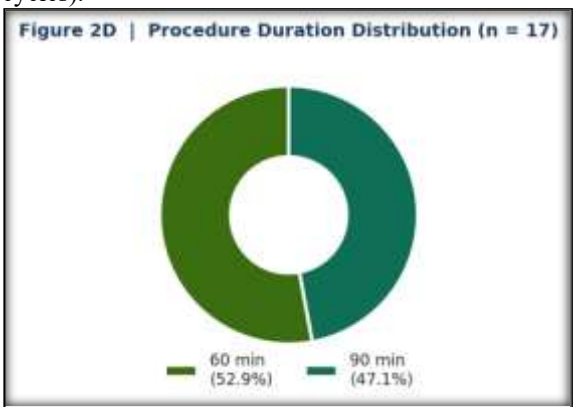


Figure 2D: Procedure Duration Distribution

Distribution of procedure duration among the 17 sessions with recorded timing: 9 sessions (52.9%) were completed in 60 minutes and 8 (47.1%) in 90 minutes, for a mean duration of 74.1 minutes.

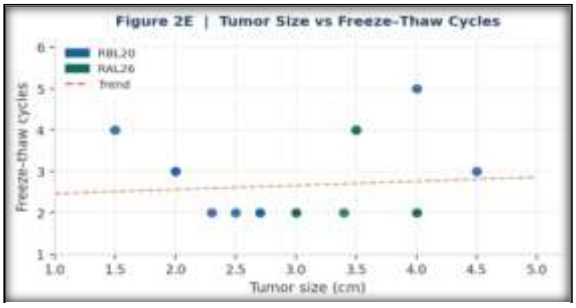


Figure 2E: Tumor Size vs. Freeze–Thaw Cycles

Scatter plot of maximum tumor size versus number of freeze–thaw cycles per session, stratified by probe type (RBL20, blue; RAL26, teal). The trend line indicates a positive association between larger tumor size and cycle number, consistent with individualized protocol scaling.

Figure 2F: Peri-Procedural Safety Outcomes

Summary of peri-procedural safety outcomes across all 18 sessions. All major complication categories — hemorrhage, cryoshock, vascular injury, and 30-day mortality — occurred at a rate of 0%. Technical success and procedure completion rates were both 100%.

DISCUSSION

This single-centre observational case series shows that percutaneous image-guided co-ablation using the HygeaCoablation AI Epic Series liquid nitrogen–alcohol cryothermal system is technically feasible and safe for primary hepatic tumors across a clinically representative size range of 1.5 to 4.5 cm, with a 100% technical success rate and no major complication in 18 consecutive sessions.

This success rate compares favourably with published benchmarks. Wang et al. reported technical success of 96.6% and 97.0% for cryoablation and RFA, respectively, in HCC ≤4 cm.[14] Dunne et al. reported 88–92% for argon-based hepatic cryoablation in a cirrhotic cohort.[15] and RFA series generally report 90–95% for lesions ≤3 cm.[16] Our complete technical success likely reflects careful case selection, operator experience with image-guided percutaneous procedures, and the freeze capacity of the liquid nitrogen system itself.

A key technical feature of this platform is its use of liquid nitrogen, reaching probe-tip temperatures near −196°C versus roughly −160 to −185°C for argon-based systems.[7,8] This supports faster, more uniform ice-ball growth, which may explain why our mean procedure time (74.1 minutes) was comparable to or shorter than durations reported for argon-based hepatic cryoablation,[17] despite our protocol's reliance on multiple freeze–thaw cycles.

Active, alcohol-driven thawing is a further point of distinction from the passive or helium-mediated thawing used in older systems. Slow, controlled thawing is known to prolong osmotic stress on freeze-injured cells and to worsen vascular and membrane injury, amplifying cell death.[6] Whether this translates into more consistent tumor necrosis than passive thawing remains to be validated with dedicated histologic or imaging-based studies.

Probe selection in our series — RAL26 for tumors generally exceeding 3 cm, RBL20 for smaller lesions, and dual RBL20 probes for the two tumors ≥4 cm — mirrors published guidance favouring

multi-probe configurations above 3–4 cm to ensure confluent ablation coverage.[18] The need for intra-procedural repositioning in one dual-probe case underscores the value of real-time ice-ball visualization for adapting technique mid-procedure. Similarly, our mean of 2.67 freeze–thaw cycles (range 2–5) is consistent with standard protocols recommending 2–3 cycles for tumors 2–4 cm in size [17], with additional cycles reserved for larger or more geometrically complex lesions.

The absence of major complications is consistent with reported major complication rates of 1–5% for modern percutaneous hepatic cryoablation.[19] Cryoshock — a systemic inflammatory syndrome historically associated with larger-bore argon probes and large ablation volumes — was not observed, in keeping with the improved safety profile of modern, more controlled ablation systems.[20] The tissue-firming effect of freezing may also confer a hemostatic benefit by tamponading small vascular injuries, potentially contributing to the absence of clinically significant haemorrhage in our cohort [21].

Comparison with Existing Literature: Direct comparison with published cryoablation literature is limited by differences in device design, patient population, tumor histology, and outcome reporting. Wang et al. reported local tumor progression rates of 4.0% and 12.5% at 3 and 12 months for cryoablation, versus 3.8% and 15.4% for RFA, in HCC ≤4 cm [14], while Dunne et al. found comparable safety profiles for cryoablation and RFA, with less pain and fever after cryoablation [15]. The early safety outcomes in our series are consistent with these benchmarks, and our 100% technical success rate supports the capability of this liquid nitrogen–based system to meet contemporary technical success criteria.

Clinical Implications: These findings suggest that image-guided liquid nitrogen co-ablation may be a useful addition to the locoregional therapy options for primary hepatic tumors, particularly given its real-time ice-ball visualization for intra-procedural margin assessment — an advantage thermal ablation modalities lack, since their ablation extent must be inferred from temperature probes or post-procedural imaging. Its freeze capacity, active thaw control, and preservation of parenchyma outside the ice-ball may be especially useful for tumors near major vasculature, where the heat-sink effect limits thermal ablation, and for patients with limited hepatic reserve in whom preserving functional liver tissue is critical.[22]

Limitations: Several limitations warrant acknowledgment. This is a retrospective, single-centre series without a randomized or concurrent comparator arm, precluding conclusions about comparative efficacy or safety relative to other ablation modalities. The sample size (18 sessions, 17 patients) is modest, limiting statistical power and generalizability. Patient age data were not available, precluding fuller demographic characterization. Systematic long-term follow-up imaging was not uniformly obtained, preventing robust assessment of local tumor progression or survival. Histologic subtype was not consistently documented, limiting subgroup analysis by tumor histology. Minor adverse events were not graded using a standardized instrument in all cases, which may have led to under-reporting. Prospective, multicentre studies with pre-specified follow-up imaging (using mRECIST or LI-RADS criteria), standardized adverse-event grading, and longer observation periods are needed to fully characterize the long-term oncologic efficacy and safety of liquid nitrogen–based co-ablation for primary hepatic tumors.

CONCLUSION

Percutaneous image-guided co-ablation using the HygeaCoablation AI Epic Series liquid nitrogen–alcohol cryothermal system achieved a 100% technical success rate and a favourable early safety profile across 18 consecutive ablation sessions for primary hepatic tumors ranging from 1.5 to 4.5 cm. Rapid liquid nitrogen–mediated freezing, active alcohol-mediated thaw control, and real-time CT/ultrasound monitoring together enabled precise and reproducible tumor coverage, with procedure duration, cycle count, and probe selection individualized to tumor size and geometry, and no major intra-procedural or peri-procedural complications encountered. These early findings support co-ablation as a technically reliable and safe, minimally invasive locoregional therapy for primary hepatic tumors. Prospective multicentre trials with standardized long-term follow-up and oncologic response assessment are warranted to establish long-term local tumor control, overall survival, and oncologic efficacy.

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