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Robotic Assisted Thermal Ablation of Liver Tumours

--Manuscript Draft--

Manuscript Number:	
Full Title:	Robotic Assisted Thermal Ablation of Liver Tumours
Article Type:	Technical Developments
Abstract:	Objective: This study aimed to assess the technical success, radiation dose, safety and performance level of liver thermal ablation using a CT-guided robotic positioning system. Methods: Radiofrequency and microwave ablation of liver tumours were performed on 20 patients (40 lesions) with the assistance of a CT-guided robotic positioning system. The accuracy of probe placement, number of readjustments and total radiation dose to each patient were recorded. The performance level was evaluated on a five-point scale (5-1: excellent-poor). The radiation doses were compared against 30 patients with 48 lesions (control) treated without robotic assistance. Results: Thermal ablation was successfully completed in 20 patients with 40 lesions confirmed on multiphasic contrast-enhanced CT. No procedure related complications were noted in this study. The average number of needle readjustment was 0.8±0.8. The total CT dose, DLP and CTDIvol for the entire robotic assisted thermal ablation were 1381.75±535.77 mGy.cm and 516.46±395.64 mGy, respectively, while the CT fluoroscopic dose (DLP) per lesion was 352.42±228.07 mGy.cm. There was no significant ($p>0.05$) dose reduction found between robotic-assisted versus conventional method. Conclusion: This study revealed that robotic-assisted planning and needle placement appears to be safe with high accuracy with the comparable radiation dose to patient.
Corresponding Author:	Basri Johan Jeet Abdullah, FRCR University Malaya Medical Centre Kuala Lumpur MALAYSIA
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	University Malaya Medical Centre
Corresponding Author's Secondary Institution:	
First Author:	Basri Johan Jeet Abdullah, FRCR
First Author Secondary Information:	
Order of Authors:	Basri Johan Jeet Abdullah, FRCR
	Chai Hong Yeong, PhD
	Khean Lee Goh, FRCP
	Boon Koon Yoong, MBBS
	Gwo Fuong Ho, FRCR, MRCP
	Carolyn Chue Wai Yim, MBBS, M.ANAES
	Anjali Kulkarni, MBBS
Order of Authors Secondary Information:	
Author Comments:	25th Mar, 2014 Editor-In-Chief European Radiology

	European Society of Radiology Dear Editor, Subject: Submission of a Manuscript for Publication in European Radiology I am enclosing herewith a manuscript entitled "Robotic Assisted Thermal Ablation of Liver Tumours" by Basri Johan Jeet et al. for consideration for possible publication in the European Radiology. The article type is considered as Technical Development. We would also like to declare that the preliminary data from this study have been presented at the European Radiology Congress at Vienna, on 6th March 2014. The detail description of the study and complete data, however, have not been published elsewhere, or accepted for publication elsewhere, or under editorial review for publication elsewhere; and that all the authors and the relevant institutes' representatives are fully aware of this submission. Thank you for your considerations on this manuscript. Yours sincerely, Basri Johan Jeet Abullah, FRCR, MBBS, AM Professor Corresponding Author
Opposed Reviewers:	Kwan Hoong Ng, PhD Medical Physicist, University of Malaya, Malaysia Professor Ng is a colleague of the lead author. We would like to avoid biases in the reviewing process.

Robotic Assisted Thermal Ablation of Liver Tumours

[1,2]Basri Johan Jeet Abdullah, [1,2]Chai Hong Yeong, [3]Khean Lee Goh, [4]Boon Koon Yoong, [5]Gwo Fuang Ho, [6]Carolyn Chue Wai Yim, [7]Anjali Kulkarni

[1]University of Malaya Research Imaging Centre, Faculty of Medicine, University of Malaya, Kuala Lumpur, Malaysia.

Departments of [2]Biomedical Imaging, [3]Internal Medicine, [4]Surgery, [5]Oncology and [6]Anesthesia, Faculty of Medicine, University of Malaya, 50603 Kuala Lumpur, Malaysia.

[7] Perfint Healthcare Corporation, Florence, Oregon 97439, USA.

***CORRESPONDING AUTHOR**

Basri Johan Jeet Abdullah

Department of Biomedical Imaging

Faculty of Medicine

University of Malaya

50603 Kuala Lumpur

Malaysia.

Tel: +603 7949 3448

Email: basrij@ummc.edu.my

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ABSTRACT

Objective:

This study aimed to assess the technical success, radiation dose, safety and performance level of liver thermal ablation using a CT-guided robotic positioning system.

Methods:

Radiofrequency and microwave ablation of liver tumours were performed on 20 patients (40 lesions) with the assistance of a CT-guided robotic positioning system. The accuracy of probe placement, number of readjustments and total radiation dose to each patient were recorded. The performance level was evaluated on a five-point scale (5-1: excellent-poor). The radiation doses were compared against 30 patients with 48 lesions (control) treated without robotic assistance.

Results:

Thermal ablation was successfully completed in 20 patients with 40 lesions confirmed on multiphasic contrast-enhanced CT. No procedure related complications were noted in this study. The average number of needle readjustment was 0.8±0.8. The total CT dose, DLP and $CTDI_{vol}$ for the entire robotic assisted thermal ablation were 1381.75±535.77 mGy.cm and 516.46±395.64 mGy, respectively, while the CT fluoroscopic dose (DLP) per lesion was 352.42±228.07 mGy.cm. There was no significant ($p>0.05$) dose reduction found between robotic-assisted versus conventional method.

Conclusion:

This study revealed that robotic-assisted planning and needle placement appears to be safe with high accuracy with the comparable radiation dose to patient.

Keywords: robot, radiofrequency ablation, microwave ablation, liver tumour, CT-guided

Key Points

1. Clinical experience on liver thermal ablation using CT-guided robotic system is reported.
2. The technical success, radiation dose, safety and performance level were assessed.
3. Thermal ablations were successfully done with average performance score 4.7/5.0.
4. Robotic-assisted ablation has potential to increase capabilities of less skilled interventional radiologists.
5. Cost-effectiveness needs to be proven with further work.

INTRODUCTION

Image-guided thermal ablations such as radiofrequency ablation (RFA) and microwave ablation have emerged as an attractive minimally invasive interventional treatment of liver malignancies both as first line and in patients ineligible for surgery. Probes are percutaneously inserted into the tumour and a volume of tissue is devitalized either by heat (using radiofrequency or microwave) or freeze (cryoablation). Accurate placement of the probe is critical to achieving not only technical success (for lesions high in the dome in small shrunken livers or large lesions requiring multiple overlapping ablations) but also vital in ensuring adequate ablation margins leading to local tumour progression [1]. Additionally patient safety is compromised with imprecise electrode placement which may lead to major complications such as pleural and gastrointestinal perforations, laceration of vessels with bleeding, or thermal collateral damage with bile duct stenosis, biloma, gastrointestinal inflammation and subsequent perforation [2].

To improve trajectory planning and targeting, surgical navigation systems have recently been adapted to the needs of interventional radiology [3-4]. The navigation systems (commonly known as the “robots”) assist in either planning and placing of the needles/probes or allow tracking the position of a surgical tool that is projected in real-time in the patient**’**s corresponding CT or MR images [5]. The aim of these CT or MR compatible robots is to increase the accuracy of needle/probe placement through 3D imaging computerized trajectory planning in arbitrary orientated tracks to improve the outcomes of interventional therapies. Further in highly inaccessible lesions that require multiple plane angulations, robotically assisted needle placement may improve access to the target by avoidance of the straight-line path of normal linear needles. Previous studies have confirmed high targeting accuracy of a

commercially available robot in phantoms and animal experiments [4] as well as in clinical settings [3, 5]. Reduction of exposure to radiation during CT fluoroscopy to clinical staff and patient is another potential benefit [3].

The goal of our study was to evaluate the technical success, radiation dose, ease of use and safety of a new commercially available CT-guided robotic system, Maxio (Perfint Healthcare, Florence, Oregon, USA) in assisting treatment planning and tumour targeting for liver tumours ablative therapy.

MATERIALS AND METHODS

This study has been granted with medical ethics approval (MEC No. 949.9) from the Medical Ethics Committee, University of Malaya Medical Centre, Kuala Lumpur, Malaysia. Informed consents were obtained from all the patients.

Patients

A total of 20 patients (40 lesions) with primary or secondary liver tumours were treated with thermal ablative therapy (August 2013 to February 2014) with the guidance of the robotic needle positioning system, Maxio (Perfint Healthcare, Florence, Oregon, USA). Ten patients had new and recurrent hepatocellular carcinoma (HCC) while the other ten patients had liver metastases. Twelve patients were treated with the RITA StarBurst radiofrequency system (Angiodynamics, Latham, New York, USA), three patients were treated with the Cool-tip RFA system (Valleylab, Boulder, Colorado, USA), and remaining five patients were treated with the Avecure microwave system (Medwaves, San Diego, California, USA). All the

lesions were <5.0 cm in maximum diameter (the average dimension of the tumour was 1.9 x 2.2 cm).

Maxio Robotic Needle Positioning System

Maxio is an image-guided, physician controlled stereotactic accessory to a CT system, intended for the stereotactic spatial positioning and instrument guide to assist in manual advancement of one or more needle based devices for CT guided percutaneous procedures such as biopsy and RFA. The system (Figure 1) consists of a treatment planning workstation which is compatible with 3D DICOM images and a robotic positioning device docked on a registration plate (InstaReg^{TM}, Perfint Healthcare, Florence, Oregon, USA), as shown in Figure 2 adjacent to the CT table during the interventional procedure. The robotic arm has five-degree of freedom to the point of interest and able to provide orbital, cranio-caudal angulations or a combination of both for thoracic, abdominal and pelvic interventional procedures.

Figure 3 demonstrates the operational flow of the Maxio robotic system for interventional procedures.

Treatment Planning and Simulation

All the thermal ablation procedures were performed under general anaesthesia. After intubation, the patients were wrapped in reusable immobiliser to minimise patient movement during the procedure. Following baseline CT scan with suspended expiration, the lesions were identified. All the patients had non-contrasted baseline CT scan except in six patients

whose lesions were difficult to be localized. The CT images were then reconstructed to 1 mm thickness and transferred to the Maxio workstation for simulation and treatment planning. The application software allows 2D and 3D visualization of the volumetric data. Once the volume of interest (VOI) was identified, the tumour was segmented to allow verification of the target volume (Figure 3a). Any deviation from the tumour margins can be manually adjusted by either cropping or adding to the target volume. The target point (centre of the tumour volume) was then defined by the radiologist on the treatment plan. The entry point (needle puncture site on the skin surface) was determined by taking into consideration any critical structures in the needle path. The operator then inputs the choice of ablation device (RFA or microwave) including the length of the probe that is going to be used. The workstation determined the orbital and cranio-caudal angulations as well as the minimum length of the probe required to complete the ablation (refer Figure 3b). The system allows maximum six probes to be planned at one go. Figure 3c shows the example of treatment plan for two different tumours. The simulated ablation maps of different probes were then displayed as an overlay on the original tumour volume, as shown in Figure 3d. The plan was carefully checked by the radiologist to avoid critical organs or bone across the trajectory prior to confirming the plan. If the margins are inadequate, the target point or the entry point can be modified.

Robotic-Assisted Needle Placement

Once the treatment plan was confirmed, the patient was positioned to the exact coordinate as determined in the treatment plan. Patient's skin was prepared for the procedure in the intended region. The skin and liver capsule along the projected path of the ablation probe was infiltrated with 10 ml of 1% lignocaine. The robotic arm was then activated and it moved

automatically to the desired location. Once the robotic arm was completely halted at its position, the radiologist placed an appropriate bush and bush holder which matching the size of the ablation probe at the end-effector of the arm. The radiologist then inserted the ablation probe through the bush and deployed the probe completely to the end of the bush (Figure 4). Upon completion of the insertion of the probe, the end effectors were detached from the probe and the robotic arm was returned to its original position.

A CT fluoroscopy check scan was performed to ascertain the location of the ablation probe within the target volume (Figure 5). Ablation therapy was then started. For multiple lesions, the process of needle insertion was repeated as determined by the treatment plan. The completeness of the ablation was determined by using multiphasic contrast-enhanced CT scan immediately after the ablation (Figure 6).

Patient Respiratory Motion Control

To optimize tumour localization, the baseline CT scan, CT fluoroscopy check scan and post-ablation contrast-enhanced scan were all performed at the end expiration of the patient with the airway disconnected from the ventilator. Further to minimise liver and hence ablation probe excursion between the end expiration (when needle placement was carried out) and the inspiration, the tidal volumes were set at high respiratory rate and high O_2 level which was considered safe by the attending anaesthetist. Muscle relaxants were used regularly (especially when doing multiple placements) to minimise spontaneous breathing of the patient so that the end expiratory phase were consistent. Failing which the loss of muscle paralysis would impair the end tidal volume and place the liver at a much lower level.

Data Collection and Analysis

The orbital and cranio-caudal angulations of the robotic arm were recorded for each lesion targeted in all patients. The numbers of adjustment of the needle to achieve satisfactory positioning within the desired tumour volume were documented. Deviations of the tip from the centre of the targeted location were also recorded.

The performance level of the overall procedures was assessed by the interventional radiologist for each robotic-assisted thermal ablation on a five-point scale (5=excellent, 4=good, 3=average, 2=fair and 1 = poor). Any complications related to the use of the robot or the procedures were also recorded.

The CT fluoroscopic dose (DLP) received by the patients during the probe placement and ablation was recorded. The total CT dose from the whole procedure including the multiphasic CT studies was also recorded as the $CTDI_{vol}$. The doses were then compared with a random historical control group of 30 patients (48 lesions) who had liver radiofrequency or microwave ablation performed by the same radiologist but without using the assistance of a robot for probe placement. Statistical analysis was performed using independent samples T-test with 95% confident interval.

RESULTS

Thermal ablation was successfully completed in 20 patients with 40 lesions confirmed on multiphasic contrast enhanced CT. No complications related to either the use of robot or the thermal ablation were noted in this study.

The total number of lesions treated in each session ranged from 1 to maximum of 5 lesions (mean of 2 ± 1). The deepest lesion was 16.9 cm while the shallowest was 4.0 cm from the skin surface. The diameter of the lesions ranged from 0.5 to 4.9 cm (mean diameter 1.9 x 2.3 cm). The lesions were all targeted successfully with the assistance of the robotic device. The orbital angulations of the robotic arm ranged from -49.40° to 65.07° (mean positive angulation was 25.05 ± 17.77°; mean negative angulation was -28.45 ± 16.02°). The cranio-caudal angulations remained 0° in 24 lesions (15 patients) while the remaining 16 lesions (5 patients) had cranio-caudal angulations ranged from -11.88° to 36.82° (mean positive angulation was 4.33 ± 8.35°; mean negative angulation was -0.79 ± 2.84°).

Readjustments of the probe were required in 12 of the 20 patients with only single repositioning in each of the lesions. The average number of needle readjustment was 0.8 ± 0.8. There were no cases of needle reinsertions required. The mean performance level rated for the robotic-assisted ablation procedure was 4.7 ± 0.5.

The total CT dose, DLP and $CTDI_{vol}$ per patient for the entire robotic assisted thermal ablation were 1381.75 ± 535.77 mGy.cm and 516.46 ± 395.64 mGy, respectively, while the CT fluoroscopic dose per lesion was 352.42 ± 228.07 mGy.cm. When compared with historical data from our standard ablation procedure without the assistance of the robotic device, the total DLP and $CTDI_{vol}$ per patient (n = 30) was 1611.27 ± 708.38 mGy.cm and 567.33 ± 398.62 mGy, respectively, while the CT fluoroscopic dose per lesion was 501.20 ± 366.54 mGy.cm. Though none of these values were significant different ($p > 0.05$), the total DLP, $CTDI_{vol}$ dose and CT fluoroscopic dose per lesion were reduced by 14, 9 and 30%

respectively. Table 2 shows the comparison of patient radiation dose of robotic-assisted versus non-robotic assisted thermal ablation procedures.

DISCUSSION

Percutaneous CT-guided intervention is an effective method for image-guided biopsy and tumour ablation. The accuracy of CT-guided needle/probe placement, which is critical for good diagnostic yield, is however highly dependent upon physician experience. Additionally presence of vulnerable anatomy (such as bowel, nerves or vessels in proximity to the target) in the needle path has low tolerance for errors in needle placement. With conventional techniques, challenging tumour targeting frequently mandate multiple needle adjustments and intra-procedural imaging, which can prolong procedure duration as well as increase patient radiation exposure and procedural risk [6-7]. Recent advances in robotically guided interventions have been successful in assisting placement of needles or related instruments for surgery and interventional procedures [8-13].

For small tumours, such as HCC which are < 3 cm, RFA has been shown to achieve results comparable to surgical resection. However its efficacy is reduced for larger tumours [14-15]. This may be in part attributable to complexity of multi-probe placement (simultaneous or sequential), which is prone to human error as well as the greater heat sink effect with larger, more perfused tumours. Accurate probe placements is thus critical for successful large volume composite ablation and tumour-free margin [1, 16].

Thus navigational software and robotic assistance may offer a tailored solution to physicians confronting a technically challenging biopsy or ablation target. Early phantom and clinical experience with robotic navigation systems suggest procedural accuracy, reduced procedure time and reduced patient radiation exposure compared with freehand techniques [3-4, 17].

The robot used in this study was a CT-compatible 3D tumour targeting and needle positioning system for interventional radiology procedures. It is an improved version of its predecessor, Robio Ex (Perfint Healthcare, Florence, Oregon, USA) which only allows 2D visualization of the axial images and single needle/probe access per treatment plan. Additionally the planning software has a multiplanar capability ensuring better delineation of the centre of the lesion can be achieved. The system calculates coordinates on DICOM images from the CT console and guides the placement of the needle accurately within the body using a stereotactic device. The depth of needle placement is pre-determined by the system but the operator still has the option of varying this for increased safety. The system can be used for tumour targeting for abdominal and thoracic interventions, including biopsy, fine needle aspiration cytology (FNAC), tumour ablation, pain management and drainage.

While MR-compatible robots have also been developed and provided many advantages such as non-ionizing multiplanar imaging with hepato-specific contrast agents and has the highest liver tumour contrast compared to CT and ultrasound, it is however, is expensive and requires all MR-compatible equipment and accessories. Hence the access may be limited and currently only useful for lesions that are not accessible by other methods [18-19].

Localisation and navigation system performed with optical or magnetic localisation spheres requires multiple skin markers to be broadly placed prior to imaging [20]. In addition, pre-

procedure import and processing of the 3D data to the robot's workstation can be complex and time consuming and occupy a lot of space in the operation room. Devices that are time consuming in terms of pre-arrangement and usage are economically unattractive and are therefore not likely to be used in daily routine. In contrast the Maxio requires minimal effort to be mounted and registered to the CT device using the InstaReg™ technology. The system is motorised and can be operated by one person. These features reduced the complexity of the robotic-guided procedure. We found the overall satisfaction with the performance of the system to be high. Even though the planning did take time, it was found to be intuitive and was compensated for by greater ease in placing the ablation probe. Further the planning software on Maxio system allows the segmentation of the tumour and subsequent selection of the ablation probe (RFA or microwave) with the pre-determined ablation volumes to be overlaid on the target tumour. This adequacy of the ablation can be checked in all 3 planes to determine successful ablation. If this is found to be in adequate, the tip of ablation needle can be repositioned or a different probe selected.

As was previously reported [3], the greater control and ease of needle placement outside the bore of the CT gantry without exposure to CT fluoroscopy dose was again a tremendous benefit. This is especially helpful in patients who are large as well as for the lesions that require more laterally access of the needle. Even though none of the patients in this study required placement of multiple probes simultaneously, we believe this system would be truly beneficial when multiple probes/needles are necessary for the treatment, e.g. Cool-tip RFA needles with switching controller. Additionally robotic-assisted interventions would be useful for those who do not have access to CT fluoroscopy during the procedures.

Although our study showed no significant differences of patient radiation dose between robotic-assisted and conventional thermal ablation, this maybe related to the expertise of the operator in this study. Previous studies noted the decreased accuracy of inexperienced operators when placement of the needles was performed manually under the guidance of CT fluoroscopy [21-22]. Certain impreciseness during the manual needle insertion is unavoidable. The continuous reassessment and repetitive adjustment of the needle orientation under the guidance of CT fluoroscopy could lead to an increase in radiation exposure to the patients as well as the attending staff. With the assistance of the robotic positioning device, the direct radiation exposure to the interventionist's hands during needle insertion could be minimized. The radiation exposure to the operators was not assessed in this study but theoretically the staff dose decreases when the CT fluoroscopy dose decreases. A randomised controlled study with a larger sample size would be necessary to confirm this.

The time to set-up the system was not specifically measured but the interval between docking the system until it was finally attached and operated was less than 10 min. The time from image registration until the treatment planning was completed took an average of another 10 min. Although there was an initial set-up time for operating the system and treatment planning, this could be compensated for by reduced need (or time) of needle repositioning using the manual method especially when placing multiple probes/needles. Future analysis is proposed to evaluate the time efficiency of the whole procedure.

A critical part of the capability of the Maxio system is in ensuring accurate co-registration of the planning datasets with liver volume at the time of needle insertion as the system is still not able to compensate for movements of the target region, especially those caused by respiration as the planned trajectory is based on a static-acquired 3D data set. This co-

registration in our practice was achieved by performing all procedures under general anaesthesia with intubation and muscle relaxants at the end of expiration with the airway disconnected from ventilator-produced consistent positing. The muscle relaxants were used regularly especially when doing multiple placements. Otherwise the loss of muscle paralysis would impair the end tidal volume and place the liver at a much lower level. The baseline CT, needle placement and post-procedure CT acquisitions were all performed at the end of expiration once the ventilator was disconnected. Others have suggested that anaesthetic manoeuvres such as high frequency jet ventilation to reduce respiratory motion significantly reduces radiation dose [23]. However these systems are expensive and require a greater skill set. Additionally to minimize liver excursion and needle movement in the cranio-caudal direction we used low tidal volumes with high respiratory rate and high O_2.

The use of robots to assist in thermal ablation may require a major change to the current workflow with additional steps to the procedure. These include docking the robotic system, importing the images from the CT console into the workstation, segmenting the tumour, planning the entry and target points, inputting the length of the needle, and finally sending the information to the robotic arm. Thus there would be a need to redefine the roles of different members of the medical team with use of robotic assisted thermal ablation. A comprehensive work flow chart with staff being well trained in operating the robot also needs to be established.

In conclusion, we present our early clinical experience of thermal ablation for primary and secondary liver tumours using an advanced CT-guided robotic system. The system showed good accuracy for percutaneous needle placement for ablative therapy with a comparable radiation dose to the historical controls. Even though these preliminary data were promising,

the study was not randomised. A randomised controlled studies with a larger sample size comparing the robotic and non-robotic-assisted thermal ablation needs to be carried out to determine the outcomes.

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TABLES LEGENDS

Table 1: Patient demography and performance evaluation of the robotic-assisted CT-guided thermal ablation for primary and secondary liver tumours (20 patients, 40 lesions).

Table 2: Comparison of patient CT dose, DLP and $CTDI_{vol}$ as well fluoroscopic dose per lesion of robotic-assisted versus non-robotic assisted thermal ablation procedures.

FIGURES LEGENDS

Figure 1: Key components of the Maxio robotic system.

Figure 2: InstaReg^{TM} docking system for the Maxio. The alphabet "R" indicates that the robot is docking at the right side of the CT gantry at which the tumour is more conveniently accessed from the right of the CT scanner.

Figure 3: Operational flow of the Maxio robotic system for interventional procedures.

Figure 4: Treatment planning and simulation on the Maxio's workstation. (a) Identification and segmentation of the first lesion (labelled as Tumor 1). (b) The pink straight line indicates the trajectory of the ablation probe from the skin surface (entry point) to the centre of the target volume (target point). (c) Segmentation of the second lesion (labelled as Tumor 2). The plan for the first lesion can still be seen as reference. (d) The indigo straight line indicates the trajectory of the ablation probe for the second lesion.

Figure 5: The intervention radiologist inserted the RFA probe to the target tumour through the bush located at the end-effector of the robotic arm.

Figure 6: CT fluoroscopy check scan to verify the location of the ablation probe within the target volume for (a) Tumour 1 (b) Tumour 2.

Figure 7: Comparison of (a) Pre-RFA contrast enhanced baseline CT scan, and (b) Post-RFA multiphasic contrast-enhanced CT scan. The ablated volume (white dashed line) can be

clearly seen on the multiphasic contrast-enhanced scan to verify the completeness of the ablation.

Table 1

Click here to download Table: Table 1 (edited).docx

Table 1: Patient demography and performance evaluation of the robotic-assisted CT-guided radiofrequency ablation (RFA) for (hepatocellular carcinoma) HCC (20 patients, 40 lesions)

ID	Age	Sex	Diagnosis	Thermal Treatment	Baseline contrast-enhanced CT scan (Yes or No)	Size of lesion (Short Axis x Long Axis)		Depth of Lesion from the surface (mm)	Angulations (Degree)				Number of Needle Insertion	Number of Repositioning / Readjustment	Performance Level (5-1 : Excellent - Poor)	CT Fluoroscopic Dose (DLP, mGy.cm)	Total CT Dose ($CTDI_{vol}$, mGy)	Total CT Dose (DLP, mGy.cm)	CT Fluoroscopic Dose, DLP per Lesion (mGy.cm)	Outcomes
						Short axis (cm)	Long axis (cm)		Orbital (+)	Orbital (-)	cc (+)	cc (-)								
1	74	M	Low rectal cancer post-anterior resection with liver metastases at segments V, VI and VI	RFA using RITA system for all the tumours	No	2.1	2.1	77.74	45.73			11.88	3	1	4	1083	753.01	1860	361	Successful ablation
						2.0	2.1	119.17	45.78		0	0								
						3.2	3.7	115.48	61.68		5.96									
2	66	M	Colorectal liver metastases at segments VII, II, III and I	RFA using RITA system for all the tumours	Yes	0.5	0.9	126.12	22.98		5.92		4	2	4	1712	1189.13	2084	428	Successful ablation
						0.8	1.2	88.67	26.15		3.23									
						1.6	2.4	43.13	20.25		0	0								
						0.6	0.6	152.64		40.78	0	0								
3	74	M	Colorectal liver metastases at segments III	RFA using RITA system	Yes	2.1	2.1	122.24	23.28		0	0	1	0	5	777	539.57	1191	777	Successful ablation
4	56	M	HCC at segment IVa	RFA using RITA system	No	1.6	2.0	76.92	29.32		9.73		1	0	5	187	169.74	1218	187	Successful ablation
5	64	M	HCC at segments VI, VII and VIII	RFA using Cool-tip system for all the tumours	No	2.7	3.5	116.33	22.77		0	0	3	1	5	495	343.99	1458	165	Successful ablation
						2.3	2.9	152.39	44.74		0.38									
						2.1	4.3	103.94	35.81		0	0								
6	61	M	HCC post segmental hepatectomy, new lesions at segments IVb and VIII	RFA using Cool-tip system for all the tumours	No	1.1	1.3	112.03	22.47		0	0	3	1	5	875	607.76	1030	292	Successful ablation
						1.3	1.4	80.49		49.4	0	0								
						1.4	1.4	94.31		30.83	17.27									
7	55	F	HCC at segment VII	RFA using RITA system	No	3.5	4.3	140.80	8.55		6.53		1	0	5	164	113.92	815	164	Successful ablation
8	46	F	Endometrial carcinoma with liver metastases at segment VII	RFA using RITA system	No	2.2	3.0	168.65	9.04		0	0	1	1	4	614	426.31	1725	614	Successful ablation
9	66	M	Colorectal liver metastases at segments V, VI, IIX, I and II	i. RFA using RITA system for lesion V, VI, IIX and I ii. RFA using Cool-tip system for lesion II	Yes	1.9	2.3	71.16	5.52		0	0	5	3	4	1597	1108.91	2699	319	Successful ablation
						1.5	2.1	111.71		21		8.75								
						2.5	3.0	127.63	24.9		0	0								
						2.1	2.2	52.78	30.6		0	0								
						1.6	2.0	107.53	24.7		0	0								
10	66	M	Recurrent multicentric HCC at segments III, VI and II	RFA using RITA system for all the tumours	Yes	1.1	1.5	78.55	39.9		0	0	3	1	4	717	497.53	2042	239	Successful ablation
						3.2	3.8	104.63	6.79		3.29									
						1.0	1.1	127.50	1.78		0	0								
11	41	F	Breast metastases to the liver at segments III, VI and VIII	RFA using RITA system for all the tumours	No	1.2	1.2	39.95	2.12		0	0	3	1	5	461	320.43	969	154	Successful ablation
						2.0	2.3	86.04	35.15		0	0								
						1.7	1.9	68.15		0.78	26.12									
12	32	F	Multiple liver metastases from gastrointestinal stromal tumour at segments VII and V/VI	RFA using RITA system for all the tumours	No	2.0	2.3	51.99	8.61		0	0	2	2	4	1446	1005.18	1996	723	Successful ablation
						1.9	2.1	98.46	29.85		20.2									
13	80	F	Liver metastases at segments VII and III	RFA using RITA system for all the tumours	No	1.3	1.4	116.55	25.57		0	0	3	0	5	1136	789.13	1554	379	Successful ablation
						1.2	1.4	126.27	0		36.82									
						0.8	0.9	73.00	48.21		0	0								
14	60	F	Liver metastases at segment IV	RFA using RITA system	No	2.5	4.2	103.76		36.01	11.68		1	1	5	284	197.33	811	284	Successful ablation

15	46	M	HCC at segment VI/VII	Microwave ablation using Avecure 14G single cycle	Yes	4.5	4.9	98.41	11.5		4.59		1	1	5	128	89.11	851	128	Successful ablation
16	54	M	HCC at segment IIX/VI	Microwave ablation using Avecure 14G single cycle	No	2.6	3.8	92.23		20.36	0	0	1	0	5	729	507.51	1142	729	Successful ablation
17	56	F	HCC at segment III	RFA using Cool-tip system	No	1.0	1.3	47.30	2.23		0	0	1	1	4	589	1312.00	701	589	Successful ablation
18	53	M	HCC at segments VII/VIII	Microwave ablation using Avecure 14G single cycle	No	2.8	3.2	88.17	1.66		12.8		1	0	5	45	31.44	1018	45	Successful ablation
19	60	F	Colorectal liver metastases at segment III	Microwave ablation using Avecure 14G single cycle	No	1.6	1.8	107.99	65.07		0	0	1	0	5	418	289.99	1080	418	Successful ablation
20	71	M	HCC at segment V	Microwave ablation using Avecure 14G single cycle	Yes	2.2	2.3	86.23	44.05		0	0	1	0	5	54	37.16	1391	54	Successful ablation
Mean						**1.9**	**2.3**	**98.93**	**25.05**	**28.45**	**4.33**	**0.79**	**2.0**	**0.8**	**4.65**	**675.55**	**516.46**	**1381.75**	**352.42**	
Standard Deviation						**0.8**	**1.1**	**30.46**	**17.77**	**16.02**	**8.35**	**2.84**	**1.3**	**0.8**	**0.49**	**504.88**	**395.64**	**535.77**	**228.07**	
Min						**0.5**	**0.6**	**39.95**	**0**	**0.78**	**0**	**0**	**1**	**0**	**4**	**45**	**31.44**	**701**	**45**	
Max						**4.5**	**4.9**	**168.65**	**65.07**	**49.40**	**36.82**	**11.88**	**5**	**3**	**5**	**1712**	**1312.00**	**2699**	**777**	

Legends:
F – Female
M – Male
HCC – Hepatocellular carcinoma
RFA – Radiofrequency ablation
CC – Cranial-caudal angle

Table 2
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Table 2: Comparison of patient CT fluoroscopic dose (DLP) and $CTDI_{vol}$ of robotic-assisted versus non-robotic assisted thermal ablation procedures.

	Robotic-assisted thermal ablation (n = 20)	**Non-robotic assisted thermal ablation (control group, n = 30)**	**Dose reduction with robotic assistance (%)**	**P-value**
Total DLP per patient (mGy.cm)	1381.75 ± 535.77	1611.27 ± 708.38	14	P > 0.05
Total $CTDI_{vol}$ per patient (mGy)	516.46 ± 395.64	567.33 ± 398.62	9	P > 0.05
CT Fluoroscopic Dose per Lesion (DLP, mGy.cm)	352.42 ± 228.07	501.20 ± 366.54	30	P > 0.05

Figure 1
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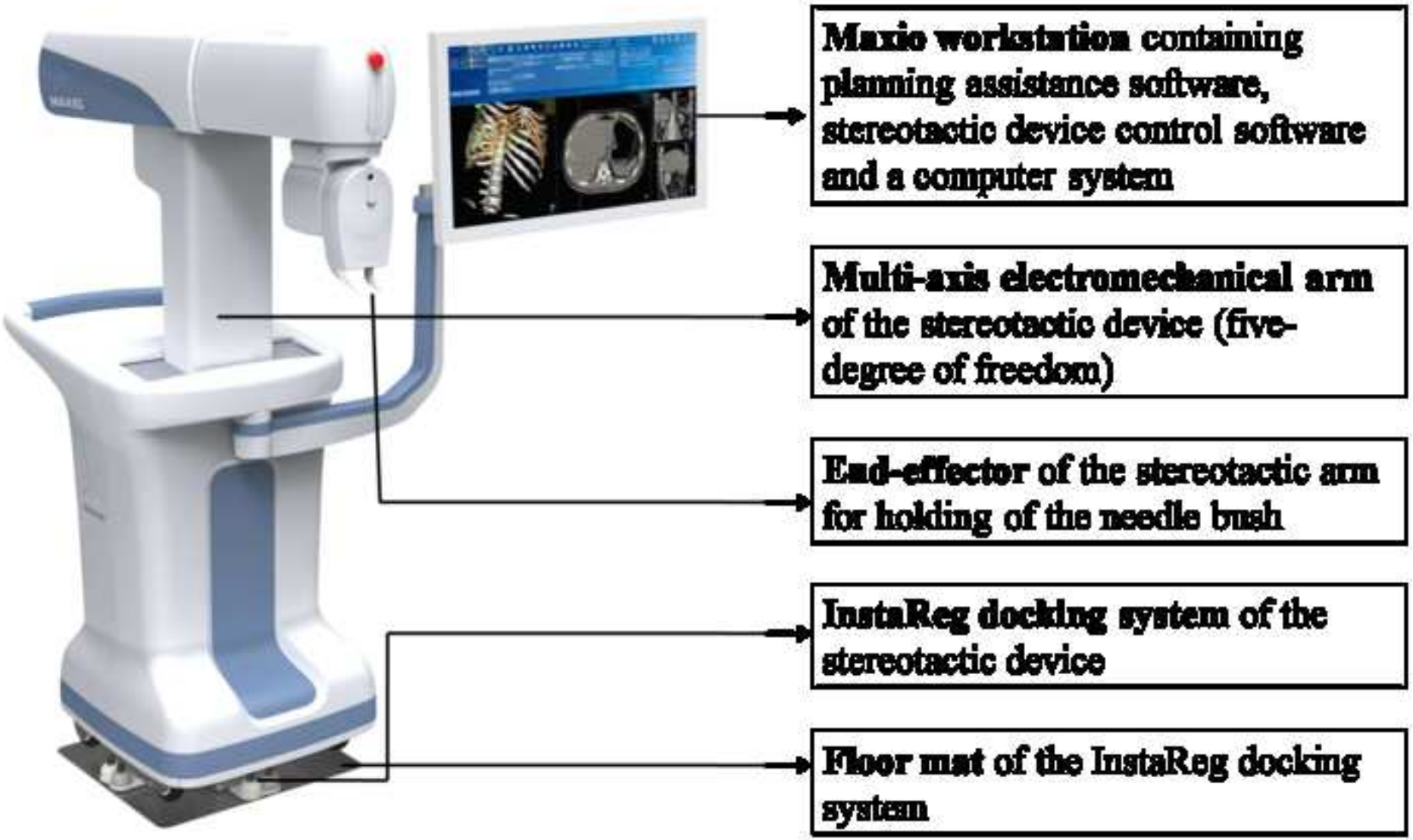

Figure 2
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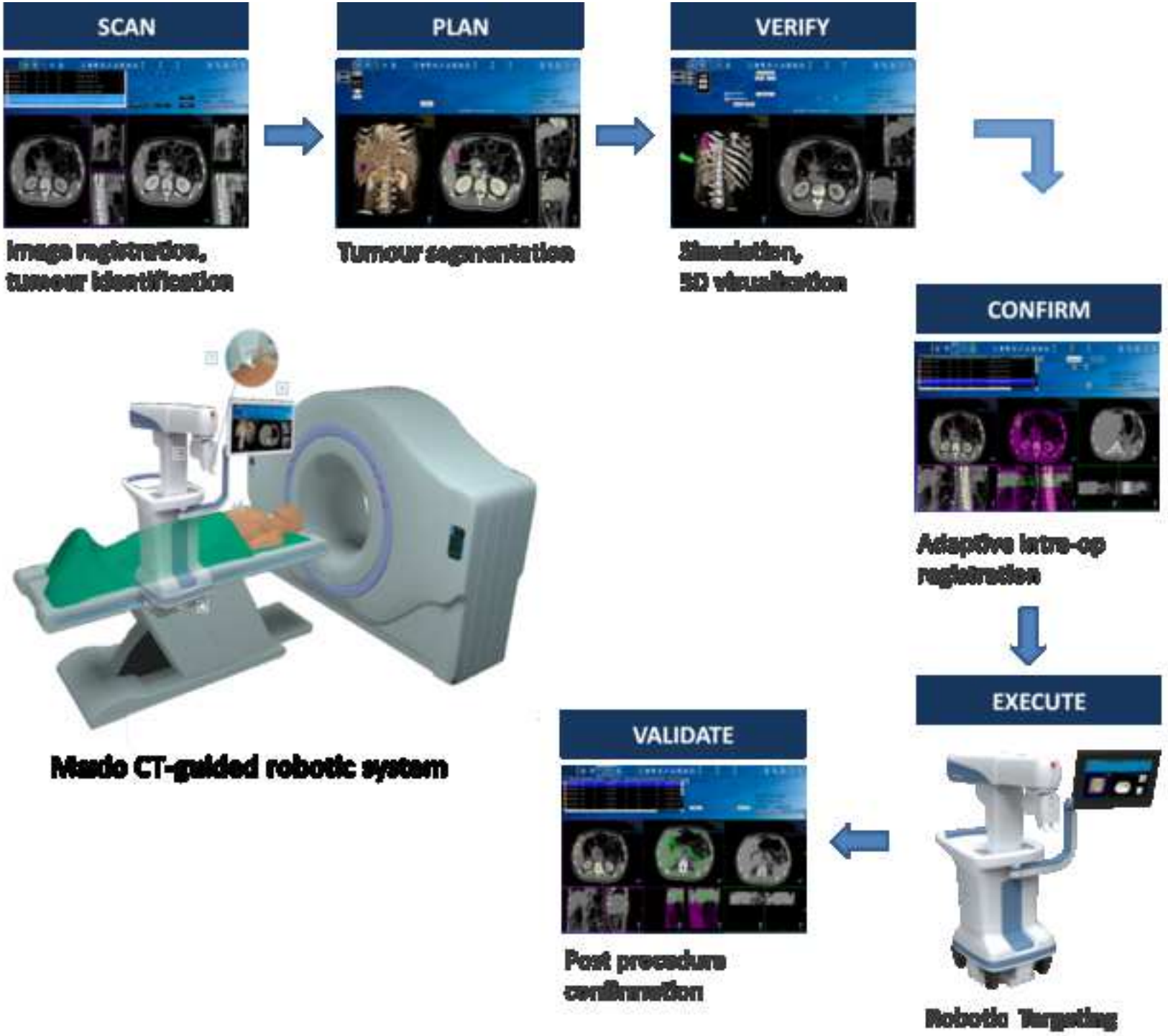

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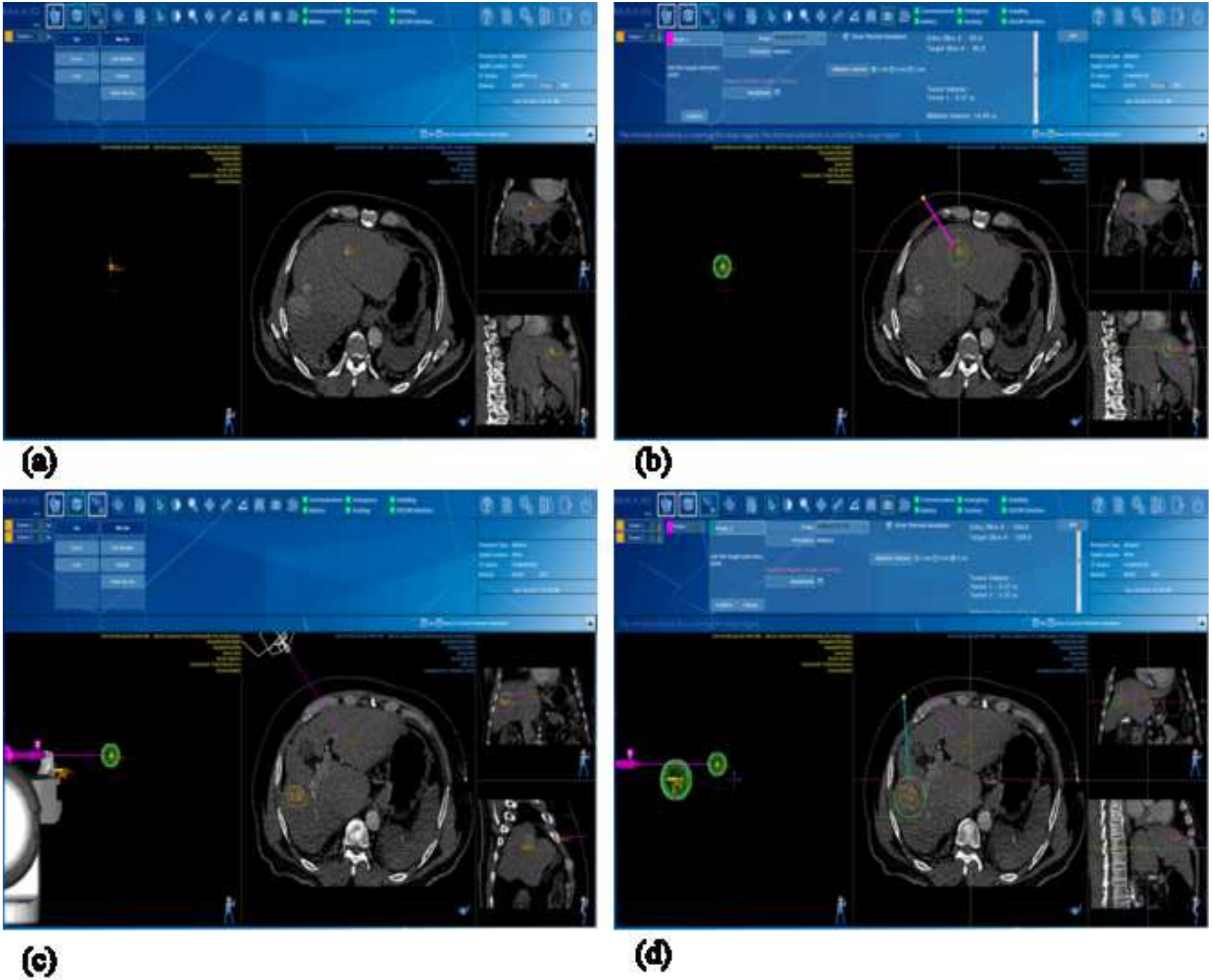

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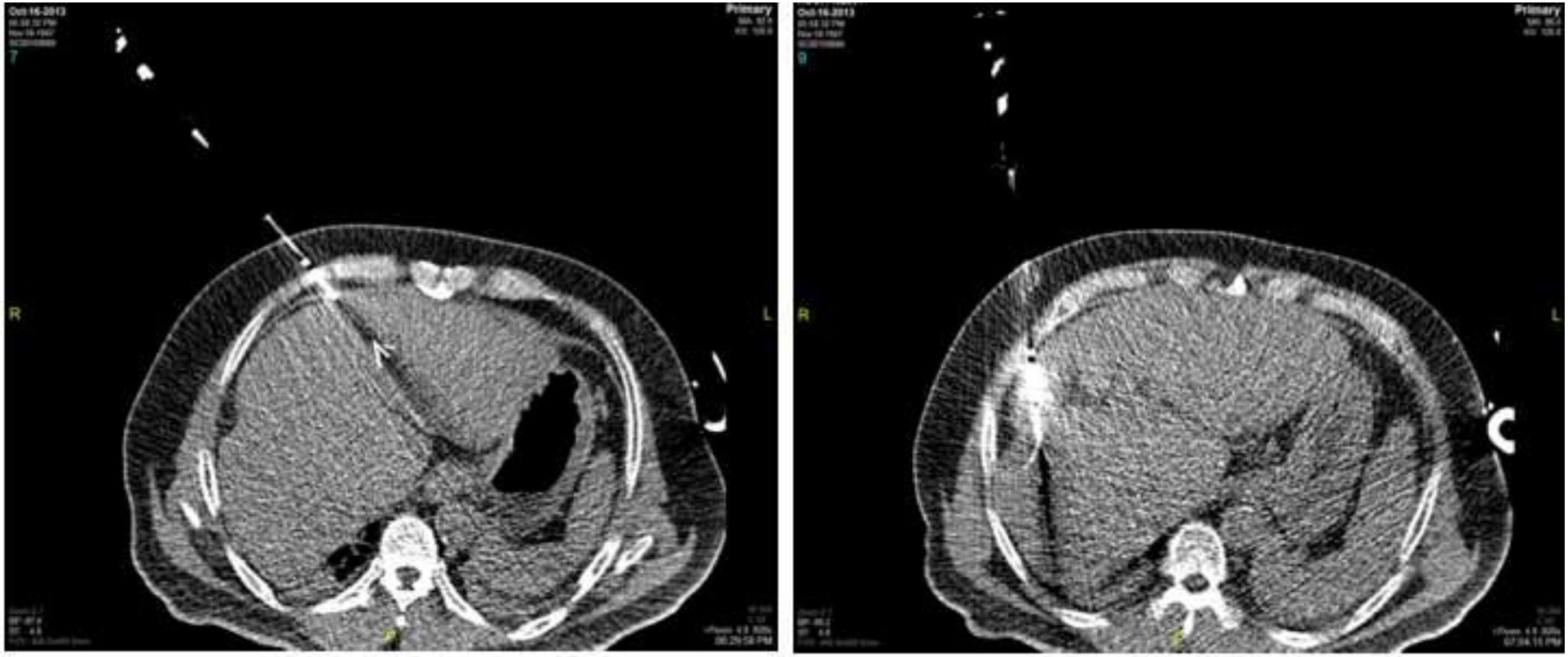

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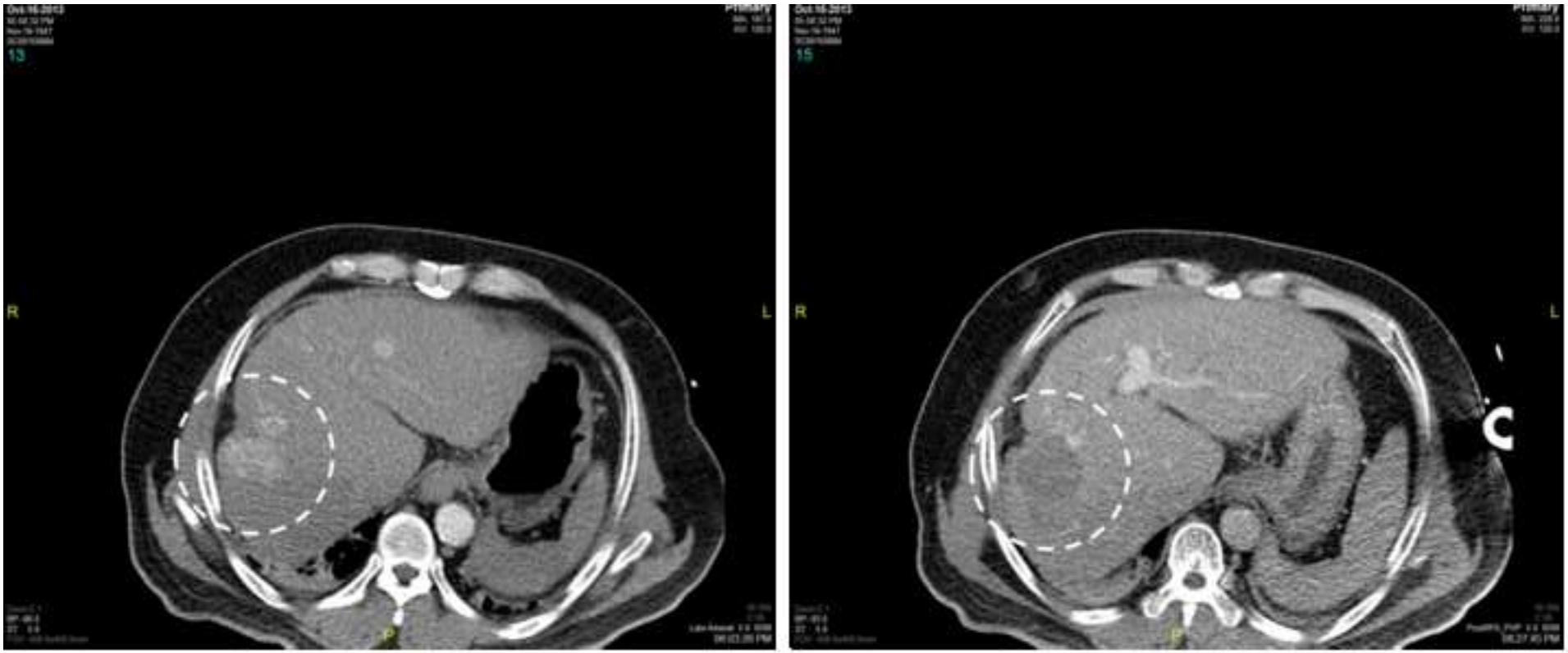

(a) Pre-RFA

(b) Post-RFA

Disclosure paragraph:

1) The scientific guarantor of this publication is Basri Johan Jeet Abdullah.

2) The authors of this manuscript declare relationships with the following companies: Perfint Healthcare Pvt Ltd, Florence, Oregon, USA.

3) The authors state that this work has not received any funding.

4) No complex statistical methods were necessary for this paper.

5) Institutional Review Board approval was obtained.

6) Written informed consent was obtained from all subjects (patients) in this study.

7) Approval from the institutional animal care committee was not required because no animal was used in this study.

8) Some study subjects or cohorts have been previously reported in the European Congress of Radiology (ECR), Vienna, on the 6th March 2014.

9) Methodology:
   - prospective
   - case-control study
   - performed at one institution

Cover Letter

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