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Implementation of surface-guided radiotherapy for motion management in liver SBRT: A scoping review and clinical workflow development

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ABSTRACT

Background: Stereotactic body radiotherapy (SBRT) is increasingly utilised for the management of primary and secondary liver cancers offering improved local control and survival outcomes. However, respiratory-induced liver motion presents significant challenges for accurate and safe treatment delivery. Surface-guided radiotherapy (SGRT) has emerged as a potential non-invasive motion management strategy, yet evidence supporting its use in this cohort is limited.
Methods: A scoping literature review was conducted using PubMed, Scopus, and CINAHL Plus to identify studies describing liver SBRT motion management, excluding abdominal compression, fiducial markers, and MRI-linac approaches. Eligible studies were identified, with results categorised by motion management approach, breath-hold method, and image guidance modality. A multidisciplinary working group developed and implemented a liver SBRT workflow integrating SGRT for both free-breathing and end-expiration breath-hold (EEBH) techniques. Motion assessment, CT simulation, treatment planning, and delivery workflows were developed.
Results: The literature review highlighted limited published data on the use of SGRT for liver SBRT. Motion assessment techniques varied between repeat 3D CT and 2D kV fluoroscopy, with assessment of reproducibility and consistency of breath-hold (BH) critical for identifying patients suitable for BH. Our centre adopted fluoroscopy-based motion assessment combined with SGRT, allowing real-time patient coaching and accurate positioning. SGRT provided streamlined workflow, and eliminated the need for additional motion management tools.
Patients unable to maintain reproducible EEBH were treated with a free-breathing internal target volume approach.
Conclusion: SGRT is a feasible and effective motion management strategy for liver SBRT, enabling reproducible EEBH leading to accurate and precise treatment delivery. It offers a non-invasive, integrated approach to patient positioning and intrafraction monitoring. Further prospective data is required to validate reproducibility of BH amplitude and clinical outcomes.

Introduction

Evolving technology has facilitated the use of Stereotactic body radiotherapy (SBRT) as an effective modality for enhancing local control and improving survival outcomes in patients with both primary and secondary liver malignancies [1–3]. The delivery of liver SBRT presents substantial technical challenges, necessitating multidisciplinary collaboration and specialised equipment. Accurate localisation of the target lesion and organs at risk (OARs) is integral to the safe delivery of each treatment fraction. Specifically, given the substantial respiratory-induced motion of the liver, motion management strategies are essential for treatment accuracy and therapeutic efficacy [4].

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Several techniques have been developed to manage liver motion during SBRT. These include abdominal compression, free-breathing (FB) phased gating, dynamic tracking and breath-hold (BH) techniques that can provide stable liver positioning facilitated through methods such as assisted breath control (ABC) and real-time position management (RPM). More recently, surface-guided radiotherapy (SGRT), which uses three-dimensional stereo photogrammetry for patient positioning and real time monitoring, enhances setup accuracy, streamlines treatment workflow, and can improve patient experience is also a potential motion management strategy.

Despite the increasing adoption of SGRT, comparative data evaluating its efficacy against conventional motion management techniques in abdominal SBRT remains limited. We herewith review the current available literature on the use of SGRT in this setting and describe the implementation of liver SBRT incorporating SGRT as a setup tool for FB and end-expiration breath-hold (EEBH) techniques at our centre. The aim of this report is to outline the rationale and practical workflow for integrating SGRT alongside fluoroscopic verification within our motion management pathway, rather than to quantitatively evaluate treatment efficiency or intrafraction EEBH reproducibility. Formal evaluation of workflow efficiency, patient satisfaction and EEBH reproducibility within this pathway is planned and will be reported in future work.

Methods

A scoping literature review of current guidelines and up to date evidence on the implementation of liver SBRT was performed using PubMed, Scopus and CINHAL Plus databases. Keywords including "stereotactic body radiotherapy", "SABR", "SBRT", "motion management", and "breath-hold" were used in the search strategy. The inclusion criteria comprised studies involving liver SABR patients treated in BH using a motion-management solution. Studies involving fiducial markers, MRI-linear accelerator systems, or FB techniques were excluded. Papers using abdominal compression were also excluded. Although abdominal compression is a well-established motion management approach for this patient cohort, it was not incorporated into the initial implementation of liver SABR at our centre, as it is primarily used to restrict respiratory motion when applied alone or to support other BH systems such as Active Breathing Control (ABC).

All identified studies were screened for eligibility following the PRISMA workflow [5]. After removal of duplicates, a total of 145 papers were identified across the three databases searched. Titles were first screened against the inclusion and exclusion criteria (Appendix 1), resulting in the removal of 75 studies. Abstracts of the remaining 70 papers were then reviewed for eligibility, from which 10 studies met the criteria for full-text review [4,6–14]. Results were subsequently categorised according to motion management approach, BH method, and image-guided radiotherapy (IGRT) modality.

A multidisciplinary working group, including radiation oncologists (RO), radiation therapists (RTT), dosimetrists and medical physicists (MP), was formed. The SGRT vendor was contacted, and technical guidance and support was provided. SGRT protocols were developed and validated for each step in the pathway including; motion assessment, CT simulation and treatment delivery. Multi-phase intravenous contrast (IVC) CT-simulation procedures were integrated into the CT-simulation protocol and a workflow for achieving the required contrast enhancement was developed. Image guidance protocols were based on previous experience and published guidelines [1,9,14–16].

Results

Literature review

Published data on the use of SGRT for liver SBRT motion management is limited, with most studies comparing SGRT values to cone beam CT (CBCT) imaging deltas [17–19]. Procedures were initially developed based on the published evidence on liver SBRT using other motion management tools. A summary of these studies is provided in Table 1. Motion assessment for evaluating patient suitability for BH formed a key aspect of the protocol and was consistently addressed across the reviewed literature. Assessments typically involved screening patients by acquiring images while they maintained BH for a predefined duration, enabling assessment of both intra and inter-BH reproducibility. The process was described as crucial for identifying patients unsuitable for BH or those with uncontrolled internal motion [6].

Two primary approaches to motion assessment were reported in the literature: repeat 3D CT imaging and 2D kV cine (fluoroscopic) imaging. Repeat CT imaging for motion assessment was used in 4 studies [8,10,11,14] and 6 [4,6,7,9,12,13] utilised 2D fluoroscopy, indicating that neither technique is consistently favoured across studies.

Fluoroscopy offers a more streamlined workflow, as BH reproducibility can be evaluated in real time. In contrast, CT-based assessments require DICOM export and analysis within the treatment planning system, adding complexity to the process [10,11]. However, fluoroscopy based motion assessment is limited by its 2D nature, which may restrict accurate evaluation of three-dimensional motion. Additionally, scheduling fluoroscopy sessions on a linear accelerator requires appointment times of approximately 45 min to accommodate imaging and motion verification, which may influence departmental throughput and should be considered when implementing similar workflows.

CT-based motion assessment presents a different set of challenges, most notably the requirement for IVC during scan acquisition. Multiphase IVC-enhanced CT imaging is essential for liver SBRT planning, as enhancement characteristics differ across contrast phases according to tumour type [20]. Acquiring images at multiple venous phases improves lesion visualisation relative to normal liver parenchyma and adjacent vasculature[20]. IVC administration carries a risk of short-term adverse reactions, such as urticarial or anaphylaxis-like responses, which may compromise a patient's ability to sustain or replicate BH [21]. This challenge is not addressed in any of the studies which used this method of motion assessment.

The number of acquisitions during BH was generally consistent across studies, with fluoroscopy-based assessments comprising five images taken during five repeated BH and CT-based assessments involved three CT simulations with three repeated BH [4,6–14]. Increasing the number of image acquisitions enhances the reliability of BH reproducibility assessment and may simultaneously improve patient confidence and technique through repetition [22]. This repeated practice arguably provides a more realistic indication of a patient's ability to sustain BH during treatment delivery.

The majority of the reviewed studies did not include rates of BH failure so comparison of techniques is limited. However, Guo et al (2023) did investigate whether BH reproducibility at motion assessment correlates to reproducibility during treatment [14]. Using Receiver Operating Characteristic (ROC) analysis, the author reported a sensitivity of 0.38 and specificity of 0.78 for reproducibility of BH at CT simulation. This leads to the conclusion that while a poor BH at simulation is likely to result in a poor BH during treatment, a reproducible BH at simulation does not guarantee reproducibility throughout treatment.

Several studies reviewed compared CT simulation and fluoroscopic assessment with external surrogate systems such as ABC and RPM to evaluate breath-hold reproducibility and the correlation between respiratory traces and internal anatomy. The evidence presented here indicates that ABC and RPM can achieve breath-hold reproducibility within approximately 2 mm under controlled conditions. However, the data supporting RPM remains comparatively limited. Importantly, outliers were consistently reported across studies, with individual patients demonstrating deviations of up to 20 mm between breath-holds. These findings highlight that although external surrogate systems can provide reproducible respiratory traces, they do not universally guarantee internal anatomical stability. This reinforces the importance of image guidance alongside motion management tools to verify alignment

Table 1
Summary of methodologies across published papers.

Author [Year] DOI	CBCT	KV Fluoroscopy	CT-simulation	2D kV	Deep Inspiration BH [DIBH]	End-Expiration BH[EEBH]
Eccles et al. [2006] *https://doi.org/10.1016/j.ijrobp.2005.05.066*	✓	✓*		✓		✓
Dawson et al. [2005] *https://doi.org/10.1016/j.ijrobp.2005.03.072*		✓*		✓		✓
Hawkins et al. [2006] *https://doi.org/10.1016/j.ijrobp.2006.03.026*	✓	✓*				✓
Zhong et al. [2012] *https://doi.org/10.1016/j.radonc.2011.11.007*		✓*		✓	✓	
Lu et al. [2017] *https://doi.org/10.1002/acm2.12220*			✓*		✓	
Lu et al. [2020] *https://doi.org/10.1002/acm2.12887*			✓*		✓	
Brown et al. [2021] *https://doi.org/10.1002/jmrs.441*	✓		✓*		✓	✓
Oliver et al. [2021] *https://doi.org/10.1016/j.adro.2020.10.023*	✓	✓ *				
Hardcastle et al. [2023] *https://doi.org/10.1016/j.phro.2022.12.004*		✓*				
Guo et al. [2023] *https://doi.org/10.1002/acm2.14045*			✓*			

*Used for motion assessment.

between external respiratory signals and internal target position.

Based on these findings, our centre chose to implement a fluoroscopy-based motion assessment technique using SGRT and a strict ± 1 mm / 1° gating window around the surrogate SGRT surface.

Table 2 provides a summary of the reported advantages and disadvantages of other motion management solutions.

Workflow development

Fig. 1 illustrates the decision tree and treatment workflow developed.

Motion management assessment

The motion management assessment workflow described in this paper was implemented on an Elekta Versa HD linear accelerator (Elekta AB, Crawley, UK). Patients are set up on the treatment couch and customised vacuum immobilisation device is moulded to the patient while they are in the intended treatment position to ensure reproducibility throughout simulation and treatment. Using a generic patient template, a surface capture of the patient in FB is taken. The patient is then coached into EEBH and another surface capture is taken (Fig. 2). The patient is instructed to repeat EEBH to the same amplitude using the RTTs guidance and the SGRT patient coaching screen (Fig. 3). Once the patient can reproduce the EEBH position to within the 1 mm and 1° SGRT tolerance for a minimum of 15 s, five kV cine images are acquired (120 kV, 16 mAs and 5.5 frames per second) using the XVI® imaging system. SGRT is used to achieve and maintain this position throughout the acquisitions. EEBH reproducibility and intrafraction diaphragm motion are assessed in all images. Respiratory motion is defined as peak-to-peak diaphragmatic motion measured on each fluoroscopy image. Motion under 2 mm is optimal but 2 mm to 5 mm is acceptable with PTV margin adjustments in the superior-inferior direction. Patients with inconsistent EEBH on the kV cine images,exhibit motion outside the SGRT tolerances or demonstrate liver motion over 5 mm, are transferred to the FB workflow.

Table 2
Advantages and disadvantages of motion management solutions currently available for Liver SBRT.

Active Breathing Control [ABC]		Real time position management [RPM]		Surface-guided Radiotherapy [SGRT]	
Advantages	Disadvantages	Advantages	Disadvantages	Advantages	Disadvantages
Widely used and available.	Requires patient compliance.	Widely used and available.	Does not monitor whole patient surface.	Monitors whole patient surface in 6DoF.	Requires patient compliance for BH.
Well supported through clinical evidence.	Additional workstation required.	Supported by published literature.	Requires accurate placement of tracking device on patients.	Can be used for set-up as well as breathing control.	Technical issues
Monitors air flow, ensuring BH accuracy.	Invasive requires nose peg and spirometer.	Non-invasive.	Uses an external surface to reproduce BH.	Non-invasive.	Gating not available across all vendors or compatible with all liner accelerator hardware
Enables gated treatment.	Equipment bulky with own computer.	No extra equipment needed for breath control.	Requires patient compliance for BH.	Removes the need for tattoo marks.	Limited data published to support use in BH.
Integrated beam hold for patient BH variation.	Uses external surface tracking for BH accuracy.			Integrated beam hold when patient misalignment occurs.	Uses external surface for BH accuracy.
				Allows for personalised regions of interest.	

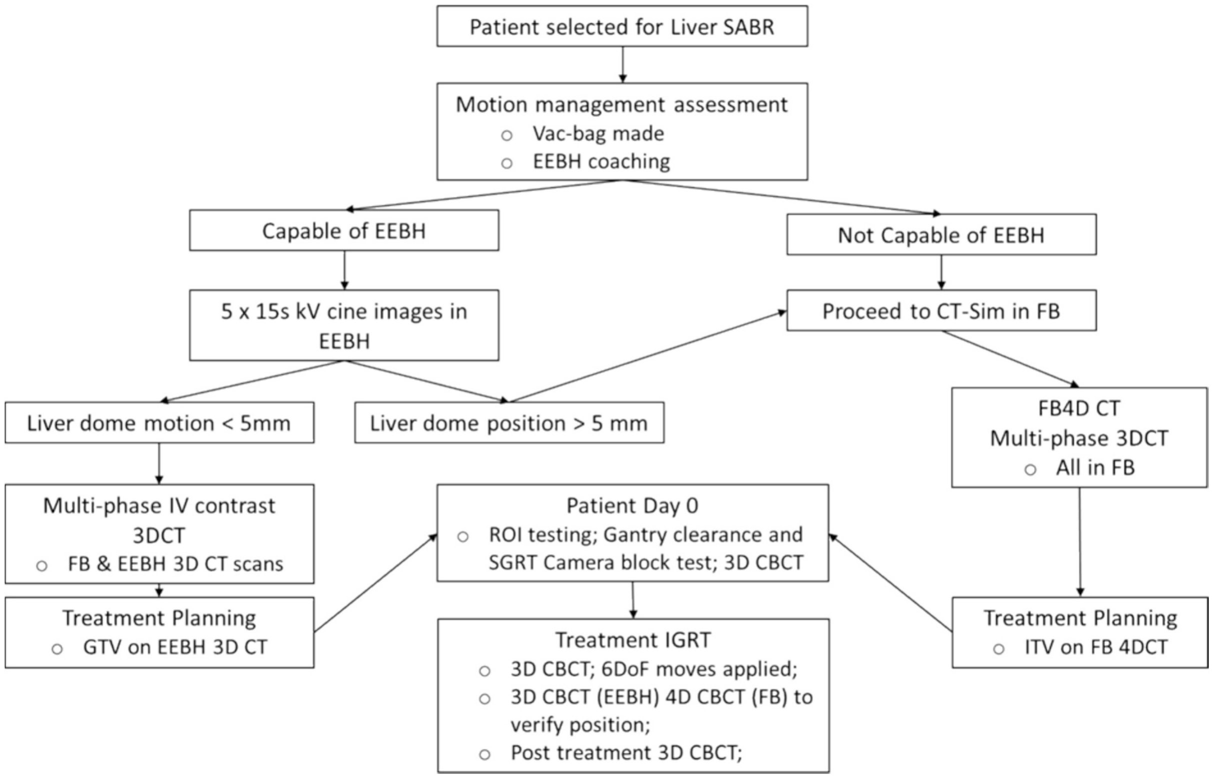

Fig. 1. Treatment Workflow Abbreviations: SABR: Stereotactic body radiotherapy; EEBH = end-expiration breath-hold; FB = Free-breathing; CBCT= Cone beam CT.

Fig. 2. SGRT surface capture with patient specific region of interest in white 1. Patient surface capture (purple) 2. Patient specific ROI (White) 3. Patient positioning deltas in 6 degrees of freedom (Vrt, Lng, Lat, Yaw, Roll, Pitch) 4. Patient breath amplitude gauge 5. Patient Plan identification 6. Treatment tools.

CT-simulation

A CT-simulation workflow described in Fig. 4 was developed which included an EEBH and FB pathway with multi-phase IVC.. At CT simulation, the patient is repositioned according to the motion assessment setup, however, a new reference surface capture is acquired. Fast CT acquisition time is crucial for EEBH patients to ensure BH is maintained throughout the scan. It is possible to reduce the duration of a CT scan by adjusting the protocol parameters. Increasing the scan pitch from 0.938:1 to 1.75:1 reduced the average CT duration for our SABR abdominal protocol to approximately 8 s,maintaining acceptable image quality. At CT-simulation EEBH and FB patients are positioned as per motion assessment, with SGRT tracking the patients breathing. The patient is monitored for a regular breathing pattern and EEBH patients are coached into a reproducible BH.

Treatment planning

OARs are initially contoured on the EEBH CT dataset by the MVision Contour+^{TM} auto contouring software and then reviewed and adjusted by a RO. The gross tumour volume (GTV) is drawn based on information from all CT-simulations, with reference to diagnostic MR or CT imaging [1]. Planning target volume (PTV) margins are recommended to be a minimum of 5 mm isotropically for linac treatments, however they should also be individualised according to motion management technique employed [21]. PTV margins of 5 mm are used when diaphragm

Fig. 3. SGRT Coaching Screen.

reproducibility is $\leq$ 2 mm, otherwise 7.5 mm superior-inferior and 5 mm radially are used to account for geographic uncertainty when reproducibility is 2 mm to 5 mm [4,12]. In all cases a multiple of the 2.5 mm CT slice thickness is used superior-inferior as per treatment planning system requirements.. If inter-BH reproducibility is unreliable or approaches 5 mm the patient is transfered to the FB internal target volume (ITV) technique with a 5 mm isotropic PTV margin added to the 4D-CT based ITV [21]. Dose volume constraints (DVCs) for OARs are primarily derived from the UK 2022 SABR consensus [23]. Priority is assigned to meeting mandatory DVCs for the liver-GTV and luminal structures followed by PTV coverage (D95% > 100%).

Coplanar VMAT plans with a single partial return arc are created using a 6 MV flattening filter free (FFF) beam, calculating dose to medium with a Monte Carlo dose calculation algorithm. Although dose rates of up to 1400 MU/min are possible, dose rates in the range of 800–1000 MU/min are common allowing for total treatment time in the range of 100 s. This allows for a rapid delivery and the completion of the treatments in 5–6 breath holds. Dose conformity is evaluated using the modified gradient index and prescription dose spillage as described in the SABR UK Consortium Guidelines 2019 and target dose inhomogeneity is kept between 110–140% [16].

Our treatment planning process was assessed during the implementation phase with the completion of the UK Radiotherapy Trials Quality Assurance (RTTQA) Group's hepatocellular carcinoma and oligometastases level 2 SBRT outlining and planning benchmarking cases [24]. Dosimetry was externally validated with the completion of the MD Anderson IROC Houston Quality Assurance Centre Liver SBRT dosimetry audit.

Day 0 & treatment

Patients are treated on Elekta Versa HD linear accelerators (Elekta AB, Crawley, UK). Image guidance is performed with CBCT acquired during EEBH, to match the target and surrounding soft tissue. Typically, no fiducial markers are used for matching although other surrogates can be used to assist with IGRT where available. Image corrections are performed in six degrees of freedom (6DoF) with the HexaPOD robotic couch. Once all corrections are applied and prior to treatment, a verification CBCT is acquired to confirm the treatment position and ensure reproducibility of the BH amplitude. For these EEBH deliveries the treatment beam is gated by the SGRT system through the Elekta Response box when the patient surface surrogate drops out of the $\pm$ 1 mm / 1° gating window around the BH. Incorporating a Day 0 appointment into the patient pathway proved beneficial, allowing for the assessment of the most suitable ROI without the pressure of delivering treatment that day. SGRT experience is also crucial for assessing camera occlusion during CBCT and treatment. This occurs when particular angles of the linear accelerator gantry physically blocks one or two of the three SGRT tracking camera pods. Whilst the system is designed to function under these conditions certain ROIs and patient anatomy can cause erroneous momentary shifts in patient misalignment deltas or even a complete loss of tracking, until occlusion ceases due to the continued motion of the gantry. In practice, camera occlusion primarily occurs when imaging panels are deployed, resulting in partial obstruction of the SGRT camera pods. To minimise the impact of this, several strategies can be employed. These include ensuring an adequate ROI across the abdomen or thorax to maintain surface tracking during temporary camera block at certain angles, appropriate skin tone selection within the SGRT system, and consistent lighting conditions.

Discussion

The literature review confirms that published data evaluating the use of SGRT for liver SBRT is limited and predominantly observational, with studies primarily comparing SGRT-reported surface displacement against CBCT setup errors rather than internal target motion [18,19].

Despite this limitation, SGRT offers several practical advantages, including non-ionising real-time monitoring, improved setup efficiency, and the ability to monitor patient motion in all 6 DoF. Our center's decision to adopt SGRT as a motion management tool was therefore driven less by evidence of direct internal target localisation and more by its ability to support reproducible patient positioning and consistent breath-hold amplitude.

The inclusion of a Day 0 appointment further strengthened pathway robustness by allowing optimisation of the region of interest and identification of potential tracking limitations without time pressure. However, challenges such as camera occlusion during CBCT and the reliance on surface surrogates for internal motion remain important considerations. Also, successful implementation relies on RTT expertise in using SGRT, including ROI optimisation, and the ability to coach patients effectively into EEBH.

A key limitation of this review is the absence of comparative BH reproducibility data between SGRT and other established motion management systems, limiting comparision against findings reported in prior systematic reviews [25,26]. Finally, uncertainty remains regarding applicability of this technique to a broader patient population, as implementation has been limited to liver SBRT patients.

Conclusion

This review demonstrates the feasibility of implementing a liver SBRT workflow incorporating SGRT for patient setup, BH coaching, and intrafraction patient position monitoring. Despite limited published evidence in abdominal SBRT, SGRT was successfully integrated as part of a motion management strategy alongside fluoroscopic motion assessment and CBCT image guidance. The described workflow has been implemented at our centre and is currently undergoing formal evaluation. Prospective assessment of treatment efficiency, patient satisfaction and BH reproducibility represents an important area for future research, and the findings will be reported in a future publication.

Ethical approval

Ethical approval was not required for this research.

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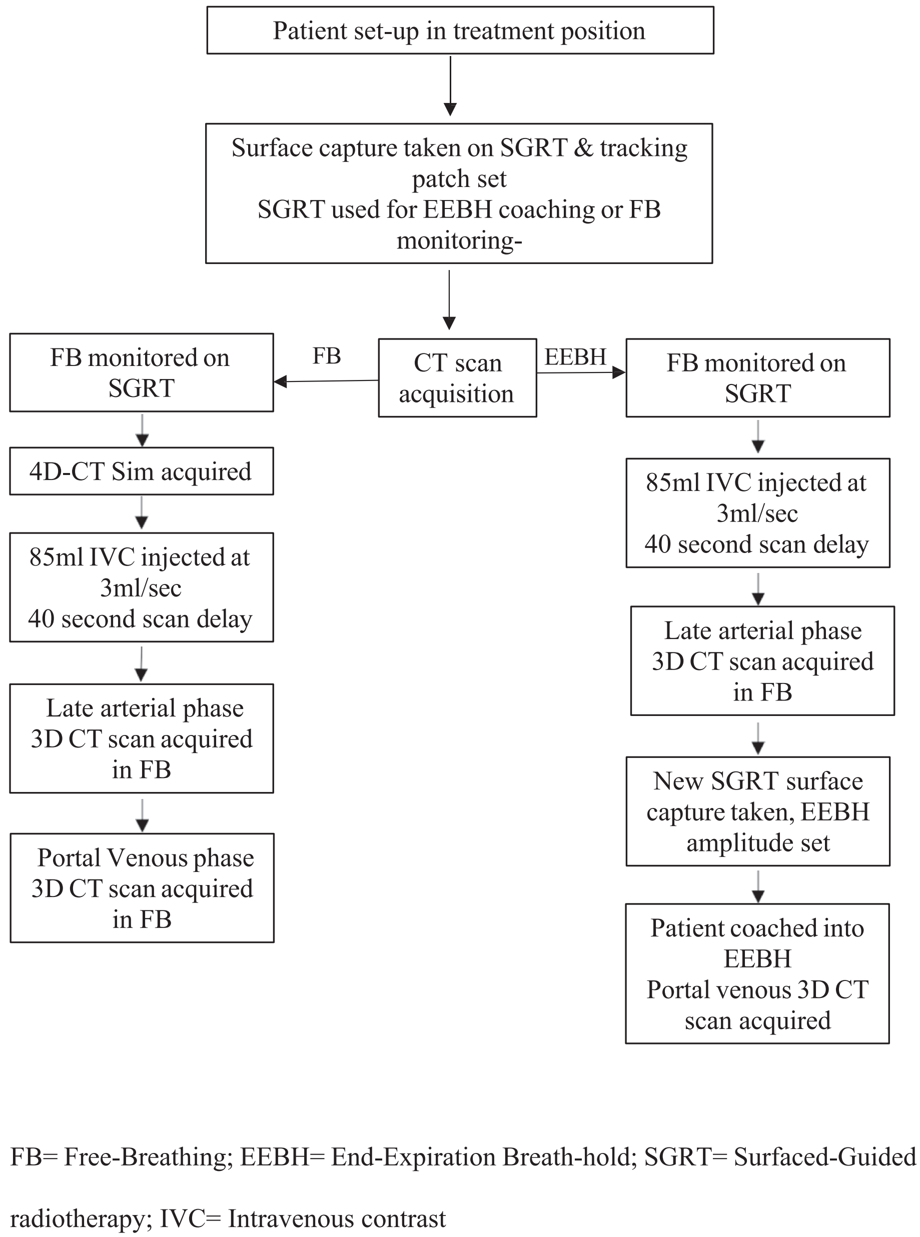

Fig. 4. CT simulation workflow for patient suitable for liver SBRT FB = Free-Breathing; EEBH = End-Expiration Breath-hold; SGRT= Surfaced-Guided radiotherapy; IVC = Intravenous contrast.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

Literature Search inclusion and exclusion criteria.

Inclusion	Exclusion
SABR treatment to the liver in BH	FB technique

(*continued on next page*)

(*continued*)

Inclusion	Exclusion
Includes data to assess the reproducibility of BH inter or intrafractionally or both	Abdominal compression
Use of ABC, RPM or SGRT	Non-English studies
	Fiducial tracking
	Dosimetry reviews

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