For SOMATOM CT users

4D CT cookbook

A guide to 4D lung CT imaging for radiotherapy planning

SIEMENS Healthineers

siemens.com/4d-ct-cookbook

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Foreword

Because organs move with the respiratory motion, CT images of the chest and abdomen may contain artifacts that create problems with reproducibility and image resolution.

The organs in the chest and abdomen move periodically and repetitively according to respiratory motion. Image artifacts and treatment risks can be avoided if respiratory motion can be precisely detected and if synchronized imaging or irradiation is available.

Especially when a linear accelerator is used for tumor treatment, normal tissue around the target may be unnecessarily exposed to radiation if the tumor is located in a moving organ. This is because the field of irradiation must be wider than the actual size of the target to account for the organ's motion.

Addressing the challenge of motion in radiation therapy is a key factor in the continuum of cancer care and External Beam Radiation Therapy (EBRT). This booklet describes current solutions and tips and tricks to implement 4D imaging in the clinical routine.

We encourage you to offer feedback that will help us support the fight against cancer.

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1. Breathing recording system

Motivation

The image quality of a 4D CT dataset depends largely on accurate scan parameters (see the ”Acquisition” section) and good synchronization between the images and the patient’s breathing curve. To help achieve high image quality, devices are used to track and record the patient’s breathing and provide this information to the user and the CT scanner.

Technologies

Respiratory gating/signal detection

There are different breathing recording systems available on the market that use different technologies. Here are some **examples**[1]:

- RPM/RGSC (Varian Medical Systems)
  Infrared tracking camera and a reflective marker block placed on the patient
- Anzai (Anzai Medical)
  Mechanical detection using an elastic belt around the patient with a pressure sensor
- Sentinel 4D CT (C-RAD)
  Laser-based optical detection of thoracic excursions
- GateCT (Vision RT)
  Surface guidance technology with tracking of the patient via single stereo camera unit

The most commonly used are optical detection systems, because some patients are uncomfortable wearing a belt around the thorax or abdomen or breathing into a spirometer.

Positioning

- The marker block’s position should be “flat” (i.e., not tilted) because many lung cancer patients don’t have sufficient thorax motion to produce a safe and robust signal (amplitude of more than 2–3 mm).
- The block should be positioned caudally from the sternum (as close as possible) and sufficiently near the target. Try to find the best location for the strongest signal.

Tips and tricks

- Some systems require an accuracy check and – if needed – a calibration prior to the first procedure each day. This procedure must be performed prior to patient setup on the table.
- Make sure that the marker block is visible in the tracked area throughout the entire scan.

Figure 1: Positioning the marker block.

Figure 2: Example of patient positioning.

[1] *The information shown herein refers to products of 3rd party manufacturer’s and thus are in their regulatory responsibility. Please contact the 3rd party manufacturer for further information.*

2. Patient selection

Motivation

Even with modern scan and reconstruction techniques, 4D CT scans are prone to artifacts and uncertainties in the observed tumor motion. In the worst case, the scan has to be aborted and then repeated, leading to extra dose for the patient. Patient selection and optional breathing training are important factors in reducing these problems.

Patient condition checklist

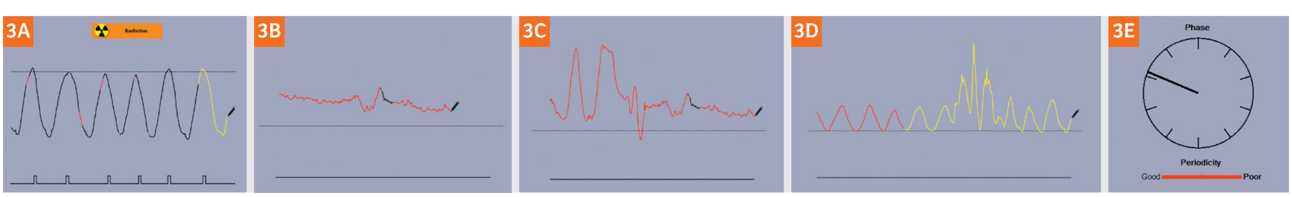
Patients with the following conditions are less suitable for a 4D CT:

- Patients who feel uncomfortable lying down for long periods
- Patients with pathological respiration patterns: for example, Biot's ataxic breathing, Cheyne-Stokes
- Patients with very long respiration periods (less than six breath cycles per minute)
- Patients with frequent severe coughing, or who are very fatigued and fall asleep during the exam
- Patients who breathe too fast (i.e., 30 bpm) -> training is needed to breathe reasonably fast

Breathing curve evaluation and examples

The breathing curve should be monitored on the breathing curve recording system. If any of the factors below occur, there may be many image artifacts or interpolations.

- Is the amplitude too low? (**3A**: ideal breathing curve, **3B**: amplitude too low)
- Is there significant irregular breathing during the 4D recording? **(3C)**
- Does coughing occur during 4D CT recording? **(3D)**
- If a quality indicator is available, does it show poor periodicity? **(3E)**



Tips and tricks

- It's important that the patient's breathing pattern is fairly regular, and coaching may make their breathing pattern more regular and lead to good 4D CT images.
- If the patient is coached for the 4D CT, coaching should be repeated for the treatment situation. Otherwise, systematic errors can be introduced: for example, the anatomy shown in the 4D CT will not represent the anatomy at treatment. If coaching is not offered, tell the patient to relax and breathe normally.
- A trial run before the scan is recommended: for example, how the table moves, how automatic patient instruction is provided.
- The optimal setup for the breathing curve recording system should be performed for the best quality indicator and amplitude. Some systems have a feature that coaches the patient: the patient can watch their breathing curve on a screen and try to follow a defined pattern.
- Some devices offer visual feedback to patients e.g. via a screen that can be used for training but also during examination. This direct feedback could help the patient to stay relaxed and guides the breathing procedure well.

3. Acquisition

Motivation

The selection of the right acquisition technique and scan parameters are crucial in order to minimize artifacts and to provide the right type of image needed for subsequent treatment planning. We describe both prospective and retrospective acquisition along with their respective pros and cons.

Sequential scan

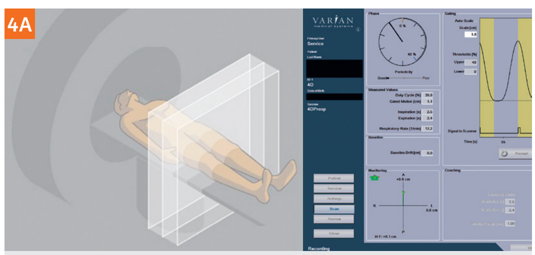


Figure 4A:
Sequential scan (prospective) can reconstruct one phase only.

Spiral scan

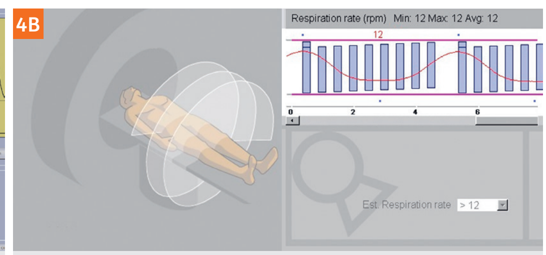


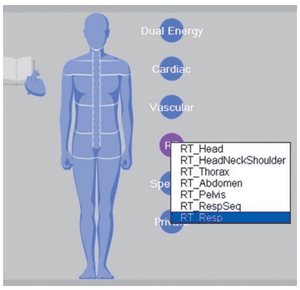
Figure 4B:
Example of the spiral scan (retrospective); phases are selected after acquisition.

	Sequential scan	Spiral scan
Radiation dose	Lower than spiral scan (because of single phase reconstruction)	Higher than sequential scan (because of multiphase reconstruction)
Robustness	Sensitive to baseline drift[1] and changes in motion patterns	Less susceptible to baseline drifts
Result	Motion frozen in one phase	Multiphase study[2] (motion visible across entire breathing cycle)
When to use	Deep inspiration breath-hold (DIBH) with gating (several breath-holds are required)	Midventilation, ITV-based contouring, T-MaxIP-based contouring

Scan protocol

When a retrospective scan protocol is selected (for example, RT_Resp), the estimated respiration rate (“Est. respiration time”) plays an important role in setting the combination of pitch and rotation time. If these parameters are set correctly, every voxel passes over the detector for at least one breathing cycle. Scanning too fast can result in missed phase information. While pitch and rotation are technical parameters, scan range is an important clinical parameter. Longer scan ranges ideally cover the entire lung so that no lesions are missed.

[1] Systematic shift of the whole respiratory curve to a higher or lower position over many breathing cycles.
[2] Multiphase reconstruction is a technique to reconstruct more than one breathing phase per acquisition. Please refer to section 4 (Reconstruction) for more details.

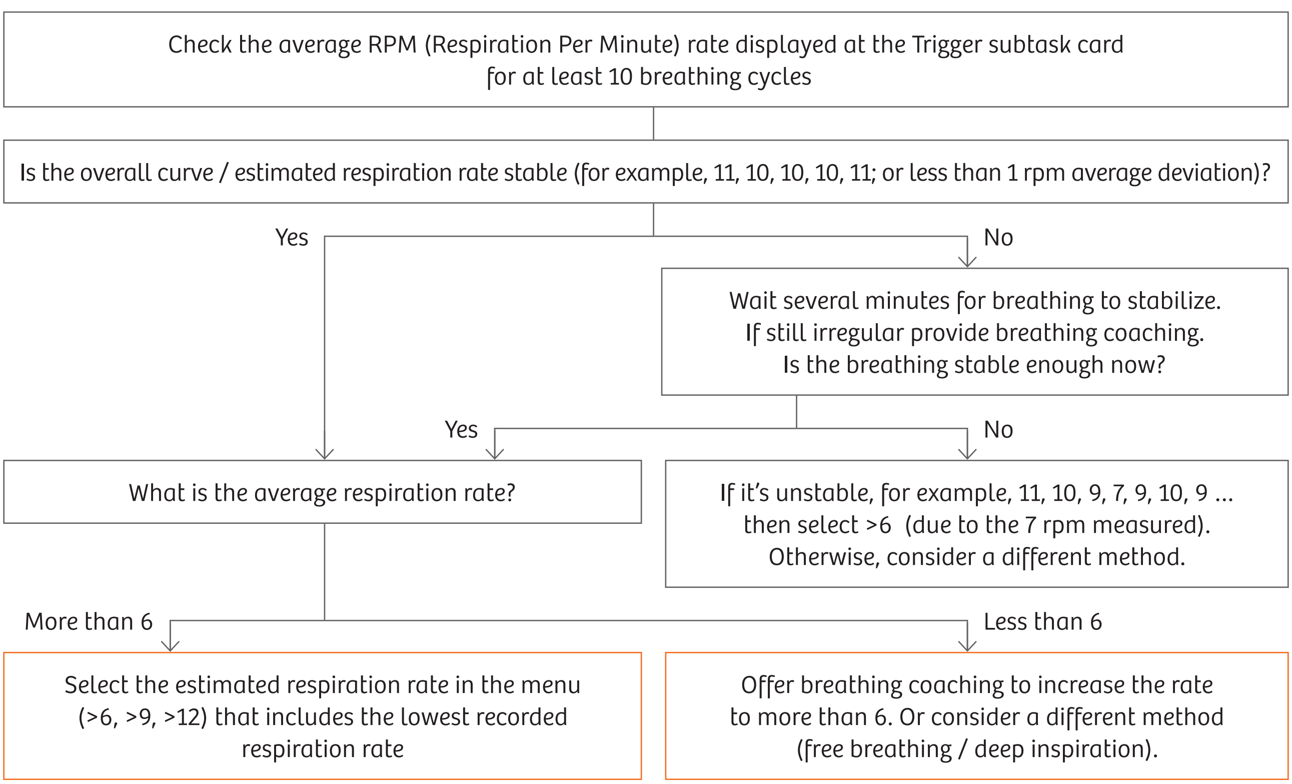


Protocol name: RT_Resp	
Scan mode	Spiral
Scan direction	Craniocaudal
Tube voltage	120 kV
mAs/rot	50

Est. respiration time	Rotation time (a) Pitch (b)	Scan length[3]
6>	a: 1.0; b: 0.09	35 cm
9>	a: 1.0; b: 0.14	50 cm
12>	a: 0.5; b: 0.09	70 cm

Respiratory motion management decision tree

After registering the patient, it's important to select the correct estimated respiration rate. The decision tree helps obtain an accurate acquisition from among the various techniques.



[3] *This may vary depending on the scanner and configuration.*

Tips and tricks

- Some breathing recording systems allow an online display of the breathing curve on the CT system; other systems require the breathing curve to be imported in order to reconstruct the breathing phases.
- The breathing curve should be given the patient's ID on the breathing recording system. This allows the file to be easily found and identified in systems where a manual import is required (this isn't required for the online methods).
- If a Varian device is used with an open interface, we recommend recalculating the peaks on the Varian device by checking "Automatic phase recalculation" and then using time-based reconstruction on the Siemens Healthineers CT.
- Please keep in mind that importing the breathing curve is required with an open interface.
- On most SOMATOM CT scanners, it's sufficient to enter the patient's respiration rate; the scanner then automatically calculates the optimal pitch/rotation time combination.
- SOMATOM CT systems (*syngo*.via VB10 required) with FAST 4D automatically detect the respiration rate from selected breathing recording systems and set the optimal scan parameters accordingly (see images 5A–5C).
- Ensure that sync is located in the correct position. Sync (shown as blue dot) is displayed at the Trigger subtask card and identifies 100% inhale and exhale.

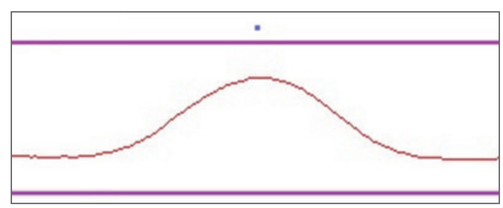


Figure 5 **5A:** FAST 4D button is visible after selecting the scan protocol.

5B: Auto check of the breathing curve is running. When successful, the load button will be active.

5C: Appropriate respiration rate and corresponding scan parameters are automatically selected and scan is performed.

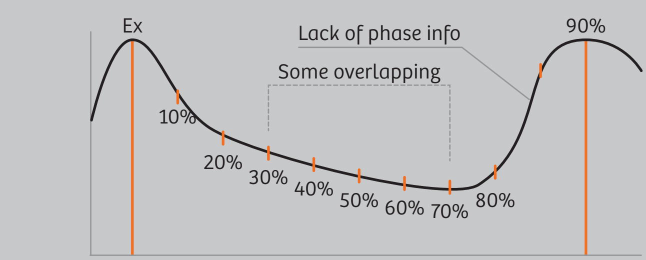
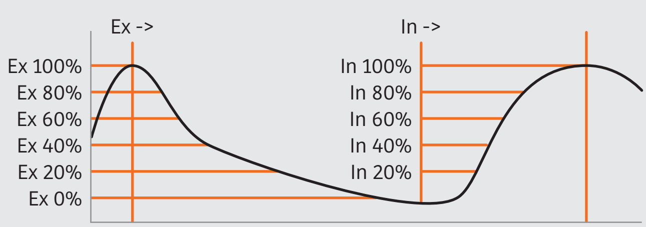
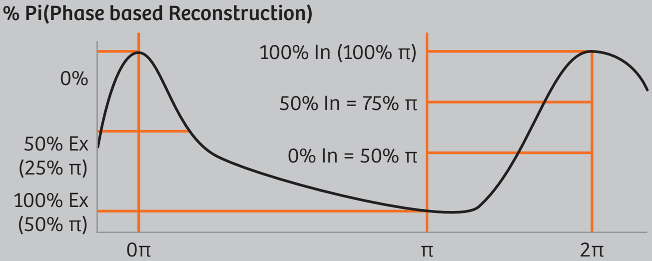
4. Reconstruction

Motivation

Reconstruction can be challenging due to patients' different respiration patterns. Inappropriate reconstruction parameters could cause changes in tumor location between the reconstructed phases due to image interpolation and artifacts.

Gating parameters (for multiphase reconstruction)

CT scanners from Siemens Healthineers offer a variety of gating parameters to match different patients' needs. Below we list their pros and cons for your clinical workflow. Today most institutions use amplitude-based reconstruction or time-based reconstruction, depending on the treatment strategy. For example, time-based reconstruction has been applied to stereotactic body radiation therapy (SBRT) planned on the mid-ventilation phase.

<table>
<tr><th></th><th>Sync Adjust[4]</th><th>Possible devices</th><th>Technique, pros and cons</th></tr>
<tr><td>%In, %Ex (Amplitude-based Reconstruction)

</td><td>✓</td><td>Anzai
RGSC
RPM</td><td>The breathing cycle is divided into equal time points.
↑ Closely depicts the actual movement of the tumor
↑ Allows calculation of midventilation phase
↓ Prone to breathing irregularities or inconsistent breathing patterns -> leading to 4D CT artifacts</td></tr>
<tr><td>Amplitude-based Reconstruction

</td><td>✓</td><td>Anzai
RGSC
RPM</td><td>The breathing cycle is divided into equal sections according to the signal amplitude.
↑ Overall artifacts are fewer when the patient has irregular breathing pattern
↑ Maximum exhalation phase can be directly reconstructed
↓ Difficult to read the actual movement of the tumor
↓ Midventilation phase can't be calculated</td></tr>
<tr><td>% Pi(Phase based Reconstruction)

</td><td>Only on RGSC</td><td>RGSC
RPM</td><td>The breathing cycle is divided into equal time points = time-based reconstruction.
→ Same results as time-based
↓ Difficult to read</td></tr>
</table>

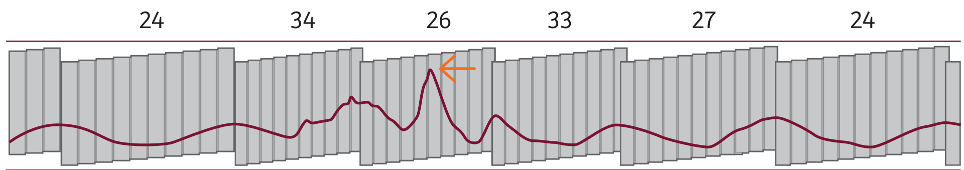
[4] *Sync Adjust is a functionality that manually shifts the sync (where 100% Exhale and 100% Inhale should be located) to the correct position if the location isn't appropriate.*

Image artifacts and troubleshooting

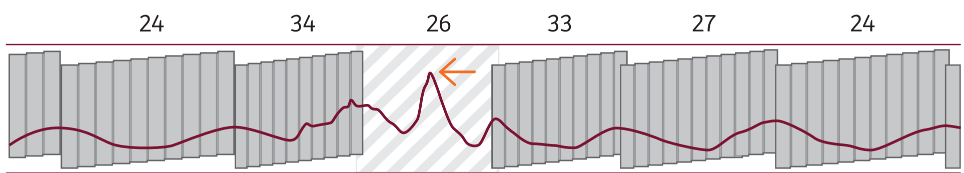
This section describes different types of image artifacts and troubleshooting to improve image quality.

Example 1:
Correction of stair-step artifacts with interpolation

Cough during the examination.
Stair-step artifacts are visible in the thorax wall.

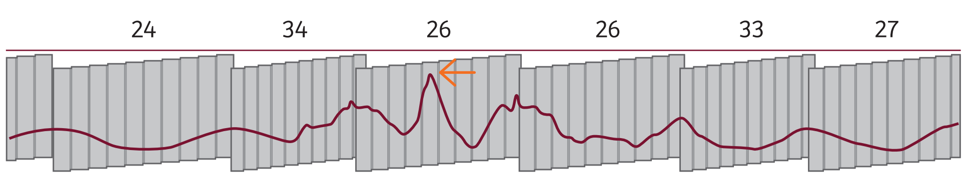


By disabling the correlating section, the image quality was improved.

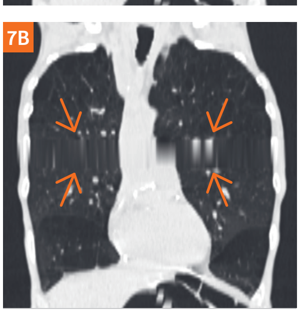


Example 2:
Stair-step artifacts are partially removed by sync removal, whereas interpolation artifacts are introduced.

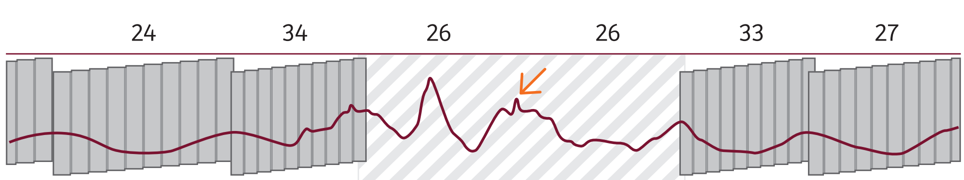
Cough during the examination.
Stair-step artifacts are visible in the thorax wall.



Respiration rate (rpm): min 23 / max 34 / avg 26



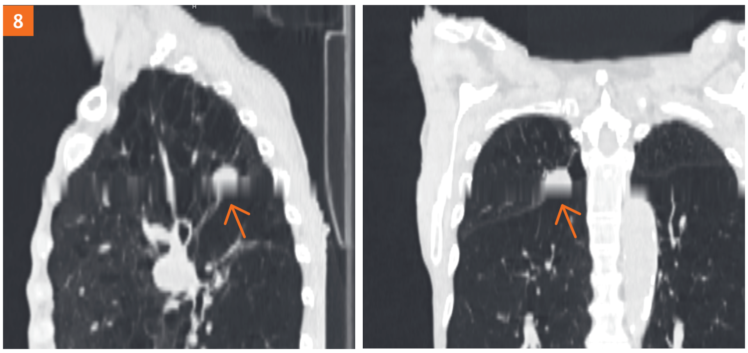
Disabling the correlating section has removed the stair-step artifacts; however, interpolation artifacts are present due to the large removed area.



Respiration rate (rpm): min 23 / max 34 / avg 26

Example 3:
Interpolation artifacts are overlapping the tumor area.

8



Tumors or small lesions inside the interpolated area aren't detected. High-quality breathing curves from well-instructed patients are necessary to obtain 4D CT data with less need for interpolation.

Tips and tricks

- Adequate breathing curve signal and proper breathing training significantly influences the quality of the imaging.
- When artifacts are present, the first approach is to identify the correct sync positions. If not, disable the problematic part.
- For areas with no respiratory activity (for example, the patient's breathing paused) or with uncommon respiration patterns (like coughing or indistinct respiratory patterns), no sync should be inserted.
- The resulting 4D CT will have interpolated data at the corresponding areas in the scan. If the volume of missing data is too large, it's possible that the reconstruction can't be performed.
- Artifacts can be prevented by coaching patients and by selecting the right respiration rate. When in doubt, choose a lower rate.

9

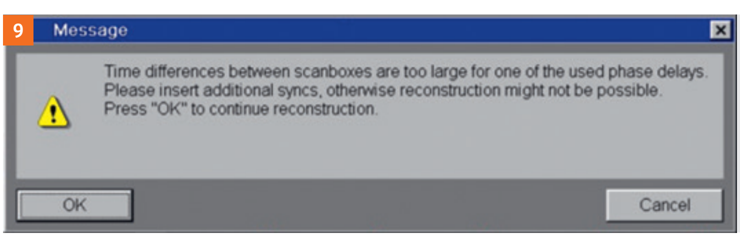


Figure 9:
Warning message informs the operator that there is too much missing data and that reconstruction may not be possible.

Reconstruction parameters

Two different reconstruction tasks are typically used in the 4D CT daily routine. The first is the Average CT. The Average CT is calculated based on the whole 4D CT (raw) dataset and represents the blurred motion image over the respiratory cycle. The second commonly performed task is to reconstruct the individual phases of the 4D CT dataset. We recommend that about 10 phases be reconstructed in order to cover the entire respiration cycle.

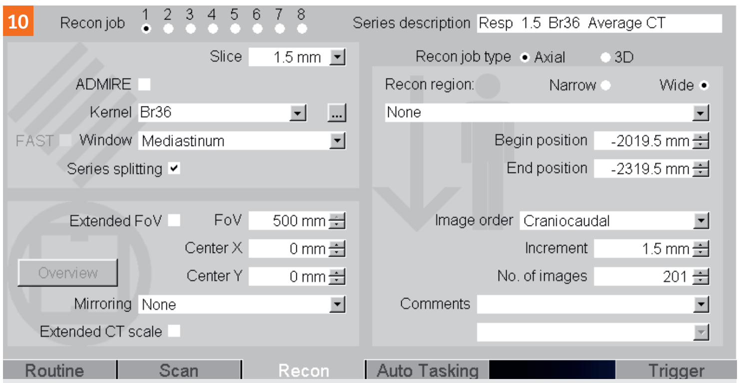


Figure 10:
Recommended reconstruction parameters

Kernel	B30/Br36
Window	Mediastinum
FOV	500 mm
Slice thickness	1.5 mm
Increment	1.5 mm
iMAR	Depends on the implants • Pacemaker • Thoracic coils • Spine implants • Shoulder implants

4D image types, advantages and disadvantages[5]

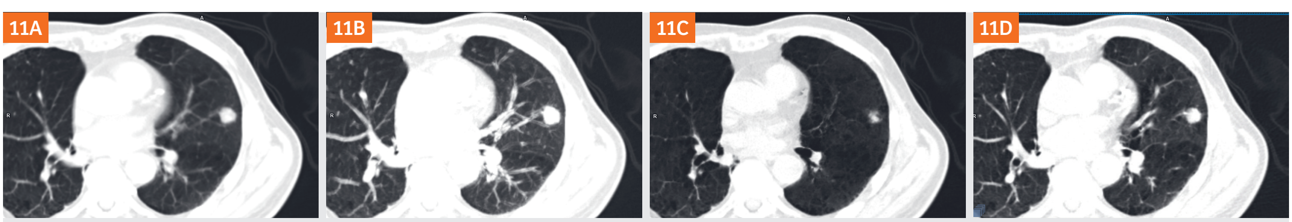


Figure 11:

11A: 4D Average CT; calculated as the average HU value over the different 4D phases.

Pros: HU stable, commonly used for dose calculation.

Cons:
- Motion blurring
- Not appropriate for target delineation.
- Using only Average CT for contouring could underestimate the tumor motion excursion.

11B: T-MaxIP; calculated as the highest HU value over the different 4D phases.

Pros: Fastest form of delineation, highlights tumors that are hyper-dense compared to the surrounding tissue.

Cons: Less accurate than the 10-phase overlap approach (iGTV). Dose calculation is less accurate than Average CT.

11C: T-MinIP; calculated as the minimum HU value over the different 4D phases.

Pros: Indicates position of tumor at all times.

Cons: Not for dose calculation.

11D: Gated phase (e.g., 10 phases from 0–100%)

Pros: Excellent view of tumor motion, sharp image for target delineation. iGTV for more accurate contouring results than T-MaxIP.

Cons: Not as smooth as Average CT because noise level is higher.

[5] *"4DCT radiotherapy for NSCLC; a review of planning methods." A. Hutchinson et al. Journal of Radiotherapy in Practice, vol. 14, issue 1, p. 70–79, (2015).*

5. Contouring target and organs at risk (OAR)

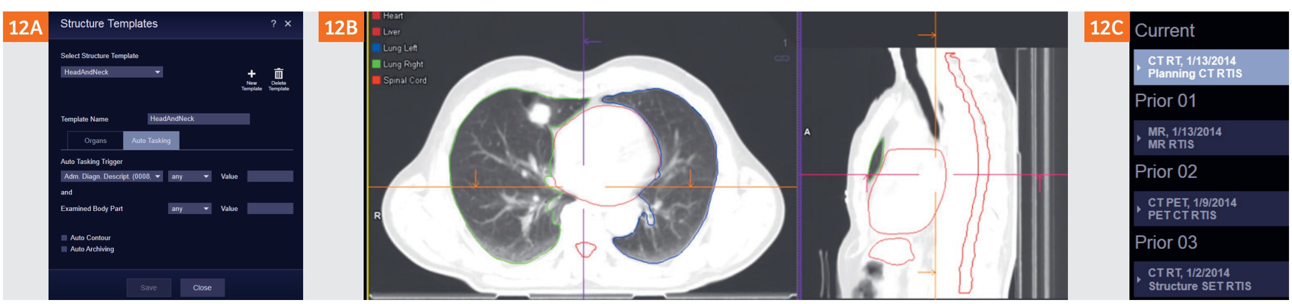
Motivation

After the reconstruction of the 4D CT dataset, the next step will be to contour the target volume and any relevant organs at risk. Traditional tools often require the user to contour slice-by-slice and phase-by-phase. This time-consuming process can be speeded up with state-of-the-art tools that use pre-processing for OAR contouring and propagation of contours across phases for fast target delineation. Modern tools can also offer insights into tumor movement patterns and help identify the midventilation phase. The workflow described here is based on use of *syngo*.via RT Image Suite.

Automatic preprocessing

With *syngo*.via RT Image Suite, the following steps are already completed by pre-processing before the case is even opened.

12A: The correct structure template is automatically selected at the scanner.
12B: Once the scan is finished, auto-contouring is triggered and contours are ready when the study is opened in *syngo*.via.
12C: Has the previous study already been performed? If so, the previous dataset is automatically loaded in the series navigator (remote prefetching).



What 4D images are used?[5]

The selection of the dataset for contouring largely depends on the motion mitigation technique that will be used in the treatment, (free-breathing, gated, breath-hold). Below is an overview of the different datasets and their pros and cons.

		Pros	Cons
Retrospective	T-MaxIP	• No specific software required • Faster than iGTV	• No tumor motion assessment • Not accurate at soft tissue boundaries • Larger PTV (tumor motion included in whole)
Retrospective	iGTV (internal gross target volume)	• Small tumors and large motion or hysteresis in motion	• Dedicated software needed for fast workflow • Larger PTV (tumor motion included in whole)
Retrospective	Midventilation[6]	• Smaller GTV & PTV (tumor motion included probabilistically in margins)	• Dedicated software needed for fast workflow • Not suitable with large hysteresis
Prospective	DIBH (deep inspiration breath-hold)	• Spare the dose to heart, coronary arteries, and lung due to increased distance between target and heart and to reduced lung density[7] • No specific software required	• Patient compliance ~75%

[5] *"4DCT radiotherapy for NSCLC; a review of planning methods." A. Hutchinson et al. Journal of Radiotherapy in Practice, vol. 14, issue 1, p. 70–79, (2015).*
[6] *"Mid-ventilation CT scan construction from four-dimensional respiration-correlated CT scans for radiotherapy planning of lung cancer patients." Wolthaus et al. Int. J. Radiation Oncology Biol. Phys., vol. 65, no. 5, pp. 1,560–1,571, (2006).*
[7] *"Dosimetric and clinical advantages of deep inspiration breath-hold (DIBH) during radiotherapy of breast cancer." Bruzzaniti et al. Journal of Experimental & Clinical Cancer Research, vol. 32, p. 1–7, (2013).*

Midventilation phase

- This represents the tumor in its time-averaged position over the respiratory cycle. The midventilation approach can help reduce the PTV, leading to potentially decreased toxicity[6]. Studies[8] indicate that, by applying smaller target volume margins, this method can potentially increase the number of patients eligible for SBRT.
- *syngo*.via RT Image Suite visualizes the quantitative 3D tumor trajectory and identifies the phase lying closest to the mid-position, making it an ideal solution for introducing this method into the clinical routine.
- Contouring on the mid-ventilation phase and applying appropriate margins for the individual patient's tumor motion can also help with locally advanced cancer patient cases, because the tumors and, thus, the irradiated volumes are large, increasing the risk of toxicity. The margin expansion can then be tailored to what is required for the specific patient, based on the tumor motion.

Figure 13:
Tumor trajectory curve shows the closest position for Midventilation.

T-MaxIP

- T-MaxIP is a projection of the highest HU value over the respiratory phases onto a 3D image at each voxel position.

DIBH

- DIBH is a technique for scanning immediately after the inspiration plateau is reached. Where spiral scans are used, the entire lung can be acquired during a single breath-hold.
- The respiratory gating device is only used for monitoring the respiratory curve.

iGTV

- iGTV is a "sum" of the GTV from all the phases. Tumor motion is covered with complete accuracy, and further consideration of the treatment strategy may be required for motion mitigation (for example, compression after large motion is indicated in the tumor trajectory).

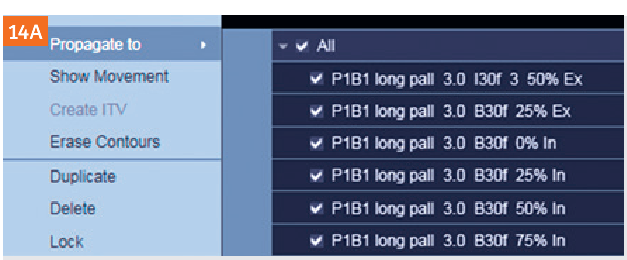


Figure 14 **14A:** After the semi-automated target delineation, contours are propagated to the other phases.

14B: After approximately 15 seconds, contours have been propagated and displayed (red dots) along with iGTV (blue).

14C: Tumor trajectory for further image assessment (e.g., decision support for treatment with a suitable motion mitigation technique, e.g., abdominal compression).

[6] *"Midventilation CT scan construction from four-dimensional respiration-correlated CT scans for radiotherapy planning of lung cancer patients," Wolthaus et al. Int. J. Radiation Oncology Biol. Phys., vol. 65, no. 5, pp. 1,560–1,571, (2006).*

[8] *"Midventilation-based PTV margins in Stereotactic Body Radiotherapy (SBRT): A clinical evaluation." Peulen et al. Radiotherapy and Oncology 110, (2014) 511–516, (2014).*

Conclusion

This booklet attempts to provide guidance for Siemens Healthineers SOMATOM CT users. The information provided is intended to support your entire clinical team in optimizing your workflow and growing your practice, while improving the prognosis for cancer patients throughout the world.

Finally, we look forward to hearing your feedback and suggestions so that we at Siemens Healthineers can continuously support you in delivering excellent care to your patients.

Acknowledgment

We are immensely grateful to Mirjana Josipovic, Medical Physicist in Rigshospitalet, who supported this paper and improved the manuscript significantly.

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Published by Siemens Healthcare GmbH · Order No. A91AT-24301-50C1-7600 · 6461 CIT12763 0818 ·