White Paper

Experience with an in-room Sliding Gantry Dual Energy CT in Particle Therapy

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Table of Contents

Introduction

The advantages of particle therapy, i.e., the localized dose distribution and the steep distal dose fall-off, are attended by an additional challenge compared to conventional photon therapy: the increased susceptibility of the dose distribution to uncertainties in the particle range and to anatomical changes.

Therefore, high-precision image guidance is even more important in particle therapy than in photon therapy. Nevertheless, to this day image guidance solutions in particle therapy still lag behind the available technologies in photon therapy.

The combination of high-precision particle therapy with in-room diagnostic CT on rails was an important step towards improved image guidance within the particle community. In contrast to cone beam CT (CBCT), the diagnostic image quality of a diagnostic CT allows for two crucial steps in image guidance: accurate assessment of anatomical changes, especially in soft tissue, and precise dose (re-)calculation.

The University Proton Therapy Dresden (UPTD) was the first hospital-based proton therapy center equipped with an in-room CT on rails, the Siemens SOMATOM Definition AS Open Sliding Gantry with Dual Spiral, sequential, dual-energy CT capability. This paper presents the center's experiences with the system during the first 1.5 years of operation.

Workflow

So far, the primary aim of an in-room CT application is to investigate inter-fractional changes of the inner anatomy (e.g., position of the target volume) for verification purposes and to assess the need to adapt treatment based on a recalculation of the nominal treatment plan. CT-based patient positioning requires an additional interface between the patient positioning system of the proton treatment system and the in-room CT, which is currently not yet available at our facility.

Patients are therefore first positioned using orthogonal X-rays and the CT is obtained thereafter, thus ensuring the same patient position on the table both during CT imaging and during subsequent treatment. This is important for retrospective dose accumulation, for example. The treatment table mounted on a robotic arm is moved from the proton gantry isocenter to a fixed position for CT acquisition (Figure 1).

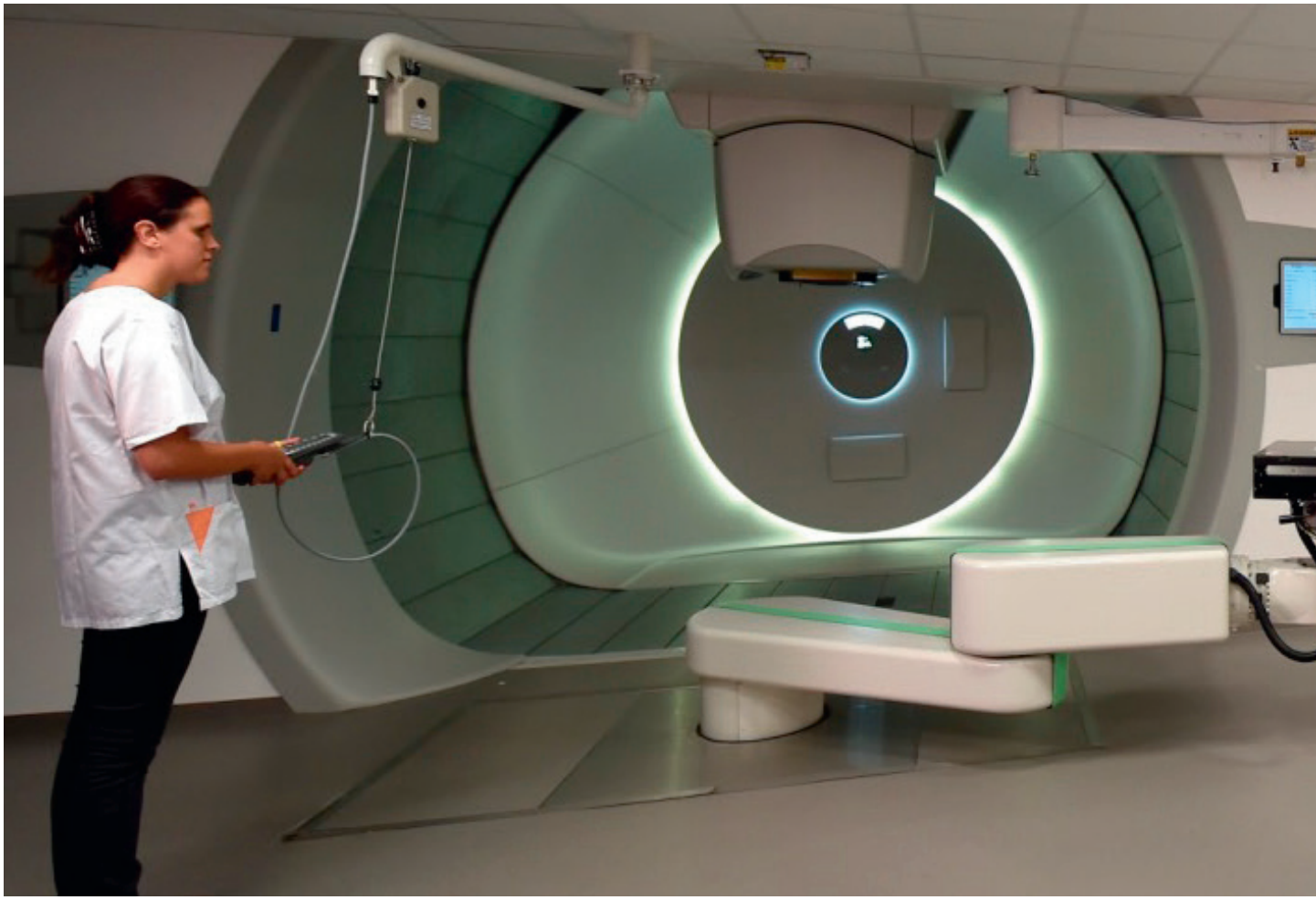


Figure 1: Installation of the in-room CT Sliding Gantry (right) next to the proton therapy gantry (left) in the University Proton Therapy Dresden (Germany).

The CT scan is acquired by sliding the CT scanner gantry along the floor rails while the treatment table with the patient stays in a fixed position. Thereafter, the patient is moved back into the proton therapy gantry and the treatment position is again verified with orthogonal X-rays to ensure the absence of patient movement during CT acquisition and table movement.

During treatment, the gantry is powered off in order to protect the electronics from neutron radiation. It takes about 3 minutes to power on the gantry before the next scan, which the workflow can easily accommodate.

In the current verification scheme, in-room control CT scans are acquired once or twice weekly for head and neck cancer patients, and once weekly for tumors in the pelvic region (e.g., prostate) – all in dual-energy mode. For non-small cell lung cancer patients, a 4D CT is acquired once or twice weekly to check for changes in tumor size, amplitude and pattern of tumor motion (e.g., baseline shifts). For other cases, such as pediatric treatment, control CT scans are acquired on the physician's request.

Evaluation of inter-fractional variations and adaptations

The in-room control CT allows for the assessment of both systematic and random inter-fractional variations.

A typical example for random day-to-day variations is target volumes in the pelvic region. In prostate cancer, the position of the prostate relative to the bony anatomy may change due to daily variations in bladder and rectum filling. Although our institution uses a strict positioning protocol including fiducial endoprostatic markers, the application of a water-filled rectum balloon, and a bladder-filling drink protocol, a weekly CT-based check of the prostate position is beneficial. The positioning is based on the bony anatomy, because the femoral heads have the biggest influence on the proton range of the two lateral fields. After a fast 6-degree-of-freedom rigid registration with the planning CT, the actual position of the prostate inside the PTV of the planning CT is verified with the help of implanted fiducials.

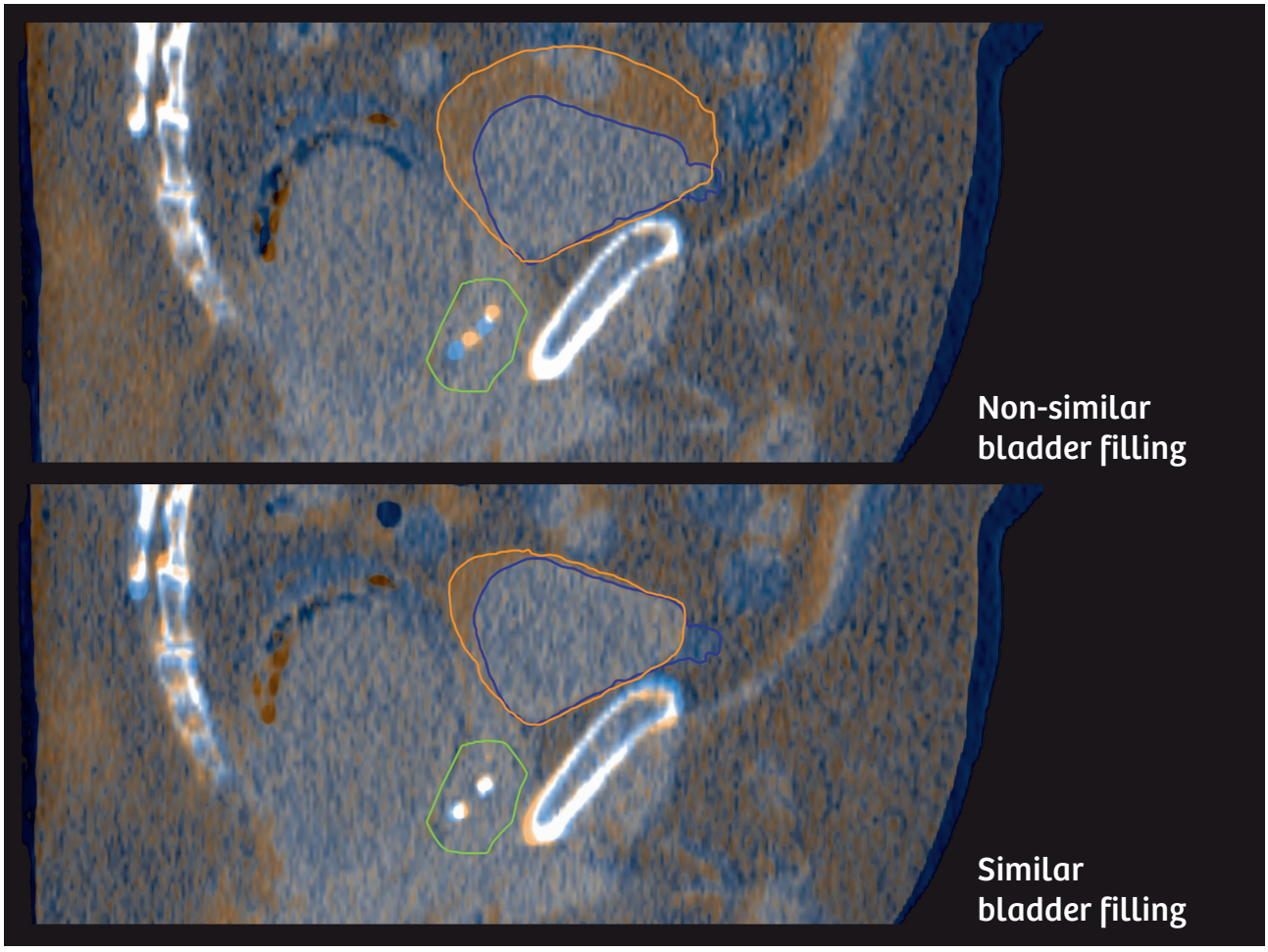


Figure 2: Example of inter-fractional variation in a prostate tumor patient for low-dose control CTs: overlay of planning CT (blue) and control CT (orange) – regions in grey do not differ between the two CTs. The bladder is contoured accordingly. In the top image the bladder volume was higher on the day of treatment compared to the planning CT, whereas in the bottom image the bladder filling was similar. The green contour highlights the marker position.

If the fiducial positions deviate more than 5 mm, an intervention is necessary. In Figure 2 the influence of the bladder volume on the prostate position is shown for a 60-year-old prostate cancer patient. On one day, the bladder volume was increased relative to the planning CT, causing a slightly different position of the prostate fiducials. After the patient had emptied his bladder and undergone the drinking protocol again, another control CT was acquired. Now, both the bladder position and volume as well as the fiducial positions between the planning and control CT were comparable and no further adjustment was necessary.

An example of a systematic change during therapy is presented in Figure 3. In this 12-year-old glioblastoma patient, a post-operative air cavity, present at time of treatment planning, had disappeared during the course of treatment, leading to a partial under-range in the proton field. After plan adaptation, the initial target coverage was recovered.

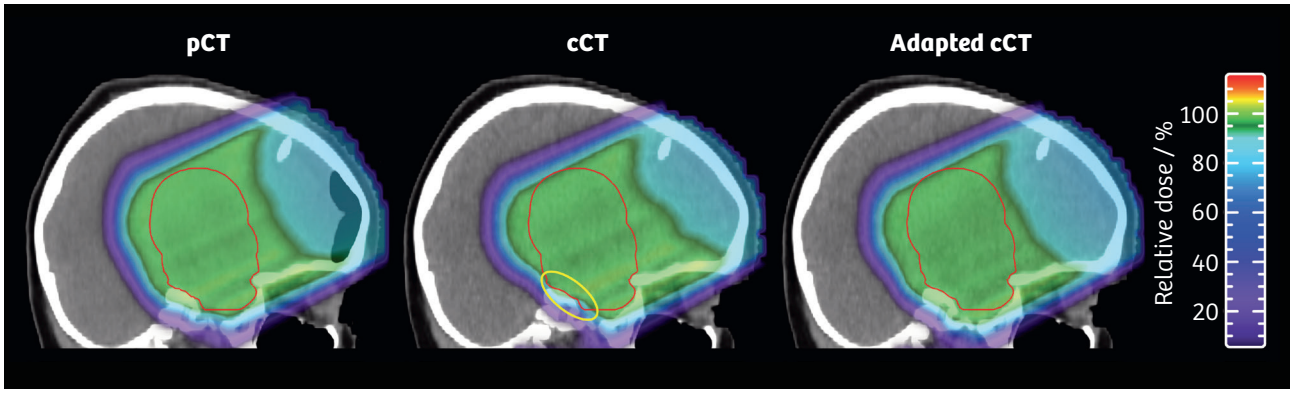


Figure 3: Anatomical changes during therapy. In this case of brain (glioblastoma) irradiation of a young child, a post-operative air-filled cavity was present at the time of the planning CT (pCT). In the control CT (cCT) at fraction 9 the cavity had disappeared, causing a severe under-range (yellow region). After adaptation of the treatment plan (right), the target volume was fully covered again. The CTV contour is represented by the red line.

The value of the SAFIRE iterative reconstruction algorithm

Because dose deposition due to repeated CT imaging during therapy is a concern, methods that potentially allow for an imaging dose reduction are of great interest. It is known that iterative reconstruction can reduce image noise compared to standard filtered back projection (FBP). However, the general image impression might be different when using iterative reconstructions. Therefore, an interdisciplinary discussion between imaging physicists and clinicians is crucial for changes in the image reconstruction protocol.

In Figure 4 and Figure 5, different iterative reconstructions with the SAFIRE (Sinogram Affirmed Iterative Reconstruction) algorithm are compared with the filtered back projection reconstruction. In Figure 4, a control CT scan of the pelvic region is evaluated. The dose for image acquisition was approx. $CTDIvol_{32\,cm}$ =7 mGy for both DECT scans together.

A clear image noise reduction is visible when SAFIRE is applied. Thus, the dose could be considerably reduced for a similar image noise level as obtained in the FBP reconstruction.

In Figure 5, a similar evaluation is shown for the brain and head regions. The influence of SAFIRE on both a control CT and a planning CT is presented. In the control CT ($CTDIvol_{16\,cm}$ of 12 mGy), a strong reduction of image noise can again be observed. In the planning CT at a higher imaging dose ($CTDIvol_{16\,cm}$ of 45 mGy), the reduction in image noise is still visible, but the gain is obviously much lower than in the control CT.

After careful interdisciplinary evaluation of the SAFIRE algorithm, the algorithm (level 3) is now routinely used in our institution for both planning as well as control CTs.

Control CT scans during radiotherapy

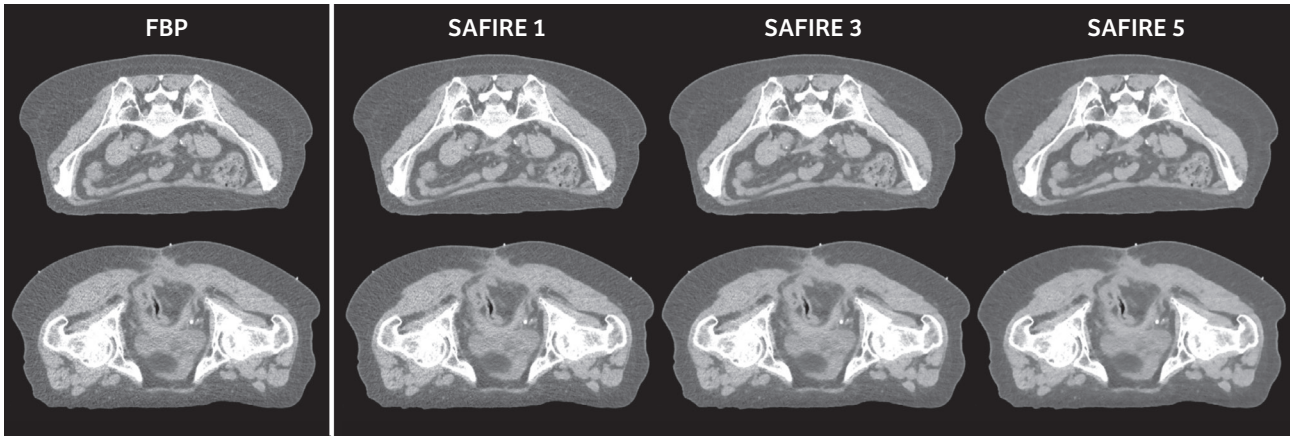
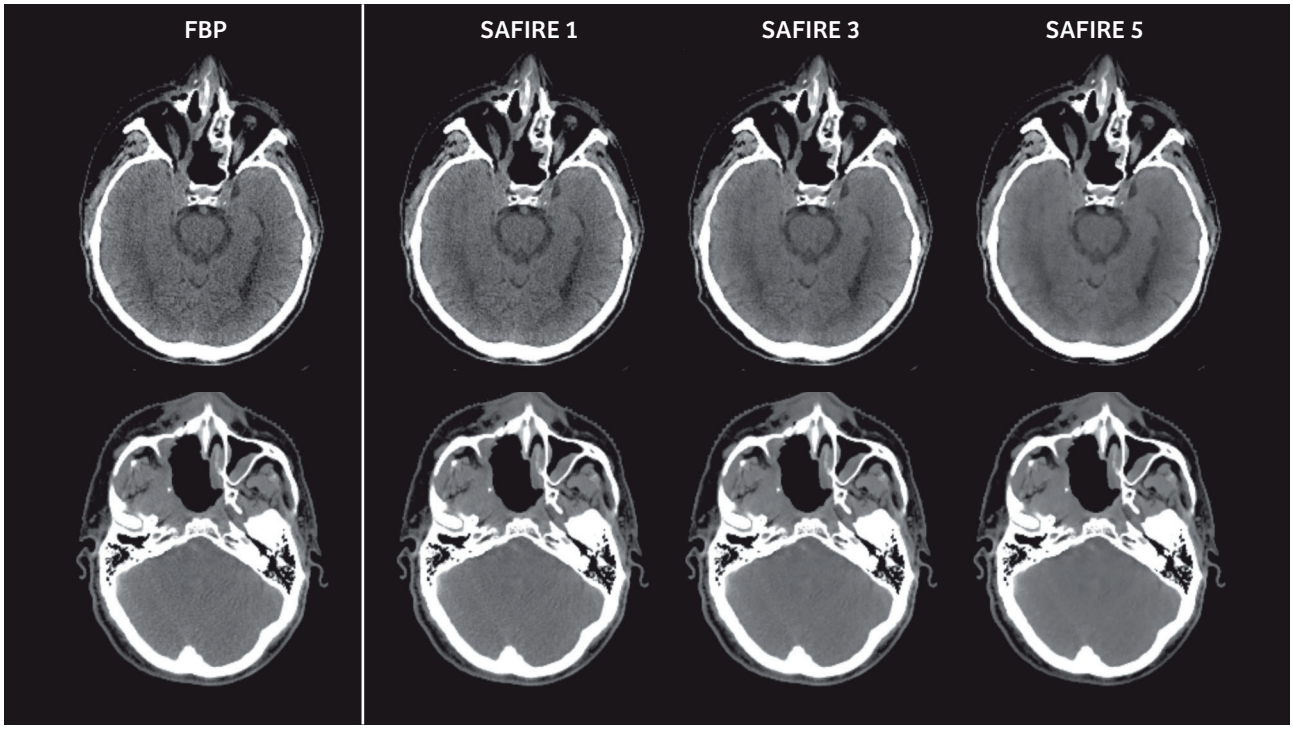


Figure 4: Noise reduction by the iterative reconstruction with the SAFIRE algorithm, applied to a control CT scan of a pelvic patient irradiated in the prone position. Three different SAFIRE strength levels have been tested. On the left, the reconstruction with the standard filtered back projection algorithm (FBP) is shown. All CT images are reconstructed from a DECT scan as a pseudo-monoenergetic CT at 50 keV using the *syngo*.via application *syngo*.CT DE MonoenergeticPlus.

CT scans for treatment planning



Control CT scans during radiotherapy

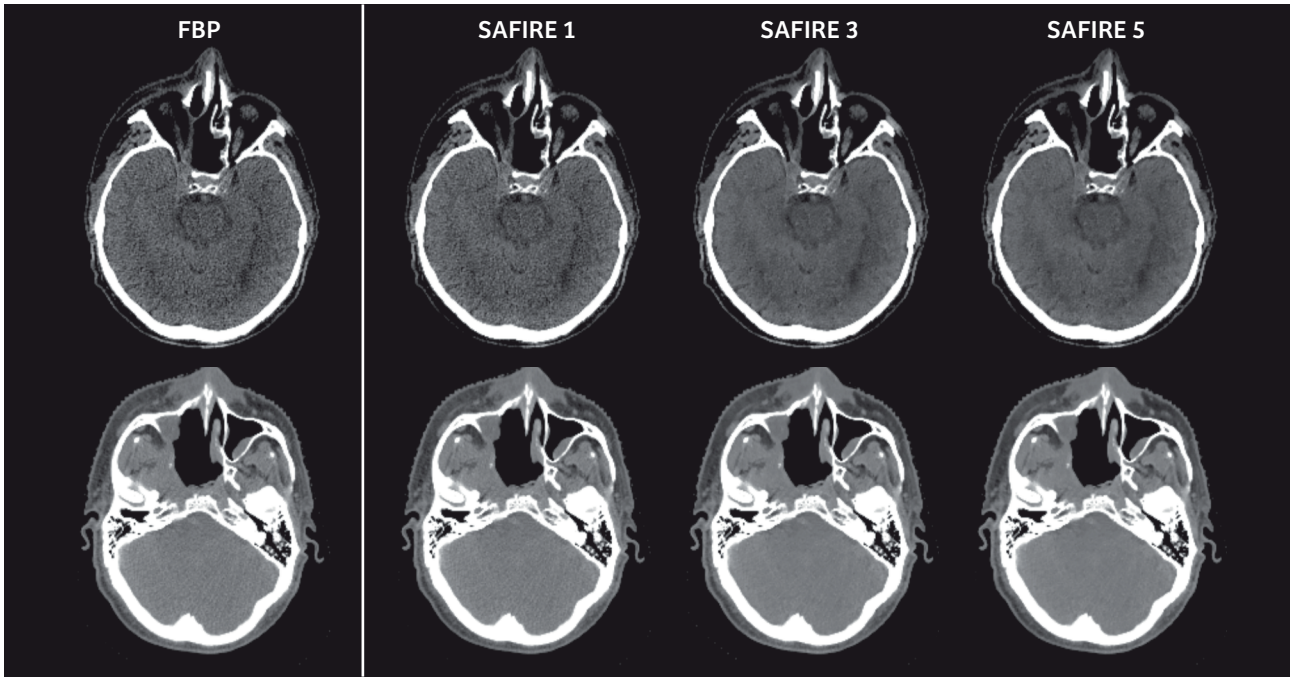


Figure 5: Iterative reconstruction with SAFIRE vs. reconstruction with filtered back projection in the brain and head region for both planning CT (top) and control CT (bottom). Three different SAFIRE filter levels have been tested. All CT images are reconstructed from a DECT scan as a pseudo-monoenergetic CT at 50 keV using *syngo*.via MonoenergeticPlus.

The value of the iMAR metal artifact reduction algorithm

Artifacts caused by metal implants (e.g., hip implants or dental prostheses) are a severe problem in particle therapy, often prohibiting a treatment with particles.

The dose and particle range calculation is very sensitive to these artifacts. Therefore, a reliable reduction of metal artifacts is even more desirable in particle therapy than it is in photon therapy.

Figure 6 shows two examples of the influence of metallic implants. Furthermore, the reconstruction with the iMAR (iterative Metal Artifact Reduction) algorithm is presented. In both cases, a clear and quite impressive reduction of the metal artifacts is prominent. Nevertheless, some streak artifacts remain in both examples. Furthermore, it was noticed that the iMAR algorithm also influences regions where no metal artifacts were present. For example, an increase in the CT numbers at the end of the tongue (dorsal) is noted when iMAR is applied. Also the shape of the tongue is changed in this region. Hence IMAR is currently used for visual inspection and contouring only. If metal implants or severe metal artifacts are in the treatment field, the patient will still be excluded from proton therapy. However, if metal implants and metal artifacts are not in the planned treatment field, patients are evaluated to receive proton treatment on an individual basis. In this case, iMAR can be applied to the CT scan used for target delineation.

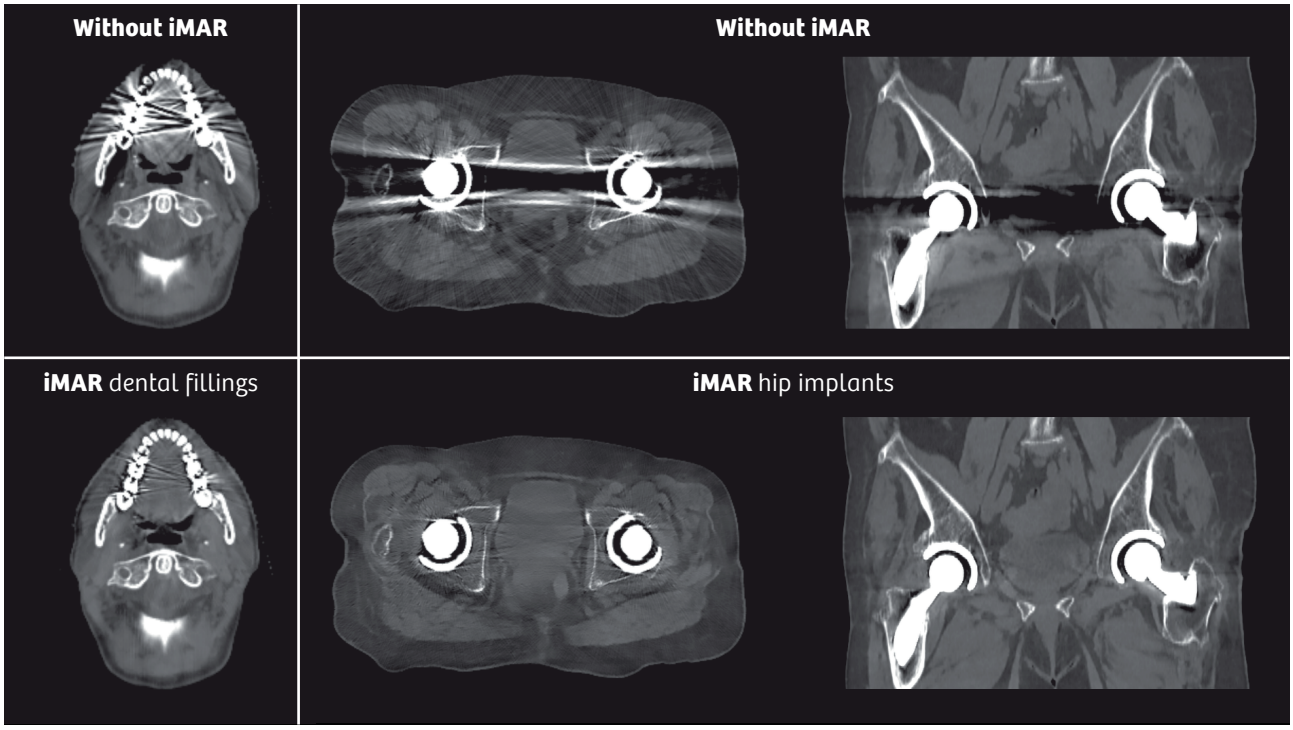


Figure 6: Influence of metal artifact reduction with iMAR for a head and neck patient (left) and a patient with hip implants on both sides (right). The same window level was used with and without iMAR. All CT images are reconstructed from a DECT scan as a pseudo-monoenergetic CT at 170 keV using MonoenergeticPlus, using the *syngo*.via application *syngo*.CT DE MonoenergeticPlus.

Future role of in-room CT in image-guided particle therapy

By far, the cases presented do not cover the whole range of applications for in-room CT in particle therapy.

For example, its application for patient positioning, not only verification of the inner anatomy relative to the treatment plan (e. g., constant localization of target volume relative to organ at risk), is already possible today. One might argue against it due to the increased radiation dose. Conversely, image guidance is gaining importance, and inferior techniques such as CBCT are already applied on a daily basis in some institutions, especially in photon beam therapy. With doses between 15-25 mGy for pelvic CBCT, the dose is even higher compared to our control CT protocol, which ranges from 5 to 12 mSv.

Moreover, the diagnostic imaging quality of the in-room CT allows direct dose calculation from the data. With the increasing importance of adaptations and calculation of the delivered dose distribution, the advantage of an in-room control CT over other more indirect techniques will not abate in the future. In contrast, when time between imaging and application of the adaptation is shortened, an imaging source that is more direct and hence more reliable and robust against potential workflow errors is beneficial.

When treating moving targets, it is crucial to verify or assess the correlation between surrogate motion and the motion of the inner anatomy. Therefore 4D CTs shortly before or after treatment with the patient in the treatment position are highly beneficial. The same is also needed for a related research topic currently attracting a lot of interest: the retrospective calculation of the actual delivered dose to assess the so-called interplay effect for treating moving targets with the pencil beam scanning technique. It requires not only the availability of the proton machine log files and a surrogate for the motion during therapy but also a 4D CT acquired shortly before or after treatment.

In summary, the foreseeable future developments in high-precision particle therapy will include faster and more frequent adaptations. In this context, in-room diagnostic control Sliding Gantry CTs will definitely play a leading role as one of the highest-quality imaging sources within the treatment room.

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