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Surface guided radiotherapy for high precision treatments of brain metastases

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Supervision

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Popularized summery in Swedish

Öppna masker och live-övervakning vid strålbehandling av hjärnan

Antalet cancerpatienter i Sverige ökar. Varje år diagnostiseras över 60 000 fall. Den vanligaste formen av cancer i hjärnan är hjärnmetastaser som uppstår då cancerceller sprider sig från den primära tumören till hjärnan. Patienter med hjärnmetastaser har en övergripande dålig prognos och bidrar signifikant till antalet cancerdödsfall. Patienterna behandlas oftast med kirurgi, strålbehandling eller en kombination av dessa två metoder.

Målet vid strålbehandling är att bestråla hela tumörområdet och samtidigt skona den friska omkringliggande vävnaden i så hög grad som möjligt. En teknik inom strålbehandling som ofta används vid hjärnmetastaser är stereotaktisk strålbehandling (SRT) vilket innebär att man behandlar små volymer med mycket höga stråldoser i få antal fraktioner. Vid denna typ av avancerade behandlingar ställs extra höga krav på noggrann positionering av patienten på behandlingsbritsen.

För att säkerställa patientpositionen krävs att patienterna fixeras. För patienter som får strålbehandling mot hjärnan används konventionellt heltäckande plastmasker som gjuts efter patientens huvud och fästs i britsen. Maskens syfte är att reproducera uppläggningen vid varje behandlingstillfälle, och samtidigt begränsa rörelser under behandlingen. Före behandling tas en verifikationsbild (3D-röntgenbild) för att kontrollera att patienten ligger rätt. Detta arbetsflöde har dock en del svagheter. Eftersom patientpositioneringen endast verifieras före behandlingen finns det inget sätt att kontrollera om patienten rör sig under tiden då strålningen levereras. Under behandlingen kan patienten röra på sig utan att detta noteras av behandlingspersonalen. Dessutom, vid SRT-behandlingar med olika britsvinklar, kan positionen endast verifieras i britsvinkel 0°. Efter verifikation och korrektion av patientposition antas att patienten är korrekt positionerad i efterföljande britsvinklar. Ytterligare en nackdel är att patienterna ofta upplever att de heltäckande maskerna är obekväma och obehagliga. Det finns alltså ett kliniskt behov av att förbättra arbetsflödet vid stereotaktiska behandlingar av hjärnan.

I detta examensarbete utvärderades potentialen att förbättra patientpositioneringen vid SRT behandlingar genom att reducera fixeringen och använda öppna masker i kombination med ett oberoende optiskt ytskanningssystem (OSS-system). OSS-systemet skannar patientens yta och beräknar patientens position i rummet. Företaget bakom OSS-systemet som används i detta arbete har nyligen släppt en ny algoritm som är specialiserad för SRT behandlingar. I studien utvärderades bland annat noggrannhet i positionering för olika britsvinklar med hjälp av ett patientlikt fantom.

Arbetets resultat visar på många fördelar med en klinisk implementering av öppna masker och OSS-systemet för SRT behandlingar. OSS-systemet kan validera patientpositionen i britsvinkel 0° med samma noggrannhet som nuvarande ”gyllene standard” för patientpositionering, och dessutom med god noggrannhet för diverse britsvinklar. Systemet kan även övervaka patientens position i realtid under behandlingen vilket resulterar i säkrare och noggrannare SRT-behandlingar.

Abstract

Purpose/Background
High accuracy treatment techniques such as stereotactic radiotherapy (SRT) requires precise patient positioning prior to and during treatment. The Catalyst™ is an optical surface scanning (OSS) system that has been utilized for patient positioning and real time monitoring during radiotherapy. The company behind the system recently released a novel algorithm for calculating the isocenter shift, specialized for SRT treatments. The aim of this master thesis was to evaluate if the OSS system with the novel SRT algorithm provides sufficient accuracy for positioning and real time monitoring of SRT treatments.

Material and methods
A study was performed using a RANDO Alderson phantom (Alderson et al. (1962) [1]), an open-face mask and the OSS system. For positioning at couch angle 0°, the agreement between the isocenter shift calculated by the OSS system and the isocenter shift suggested after image-verification with Cone-Beam Computed Tomography (CBCT) was evaluated. For non-coplanar treatments the accuracy of positioning and monitoring was evaluated by isolating the couch offset and the uncertainties in the OSS systems calculation of the isocenter shift. Furthermore, an evaluation of the dosimetric effect of patient positioning uncertainties in clinical non-coplanar SRT treatment plans was carried out.

Results
The agreement between the OSS system and the CBCT system for different tumor positions were within 0.5 mm in the longitudinal direction and within 0.3 mm in the vertical and lateral directions. For all rotational directions the agreement were within 0.9°. The OSS system indicated that when rotating the couch used in this study, the position of the phantom relative to the treatment isocenter was shifted up to 1.2 mm. The couch rotation offset were larger for larger couch angles, although within 0.6 mm. The OSS system's uncertainty in the calculation of the isocenter position was within 0.5 mm. Within this study, the worst-case scenario for current workflow entails a risk of a 21.6% decrease of V(95%). However, with the OSS system as a complement for positioning the worst-case scenario would instead be limited to a 11.1% decrease of V(95%).

Conclusions
The OSS system evaluated within this thesis has the potential to improve patient positioning for SRT treatments. It has been concluded that the OSS system with the novel SRT algorithm show excellent agreement with the CBCT system and has the ability to validate the position of a phantom with 0.5 mm accuracy, at all couch angles. When tracking the surface, the only additional uncertainties are the motion and deformation of the surface. Thus, the OSS system has no problem monitoring the phantom position. However, the system must be further tested on volunteers and patients before clinical implementation, for which there will be some surface motion and deformation. This master thesis is the first step towards commissioning of the OSS system and open-face masks for SRT treatments in the clinic.

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Abbreviations

VMAT Volumetric Modulated Arc Radiotherapy

SRT Stereotactic Radiotherapy

OSS Optical Surface Scanning

CT Computed Tomography

CBCT Cone-Beam Computed Tomography

SRS Radiotherapy Radiosurgery

WBRT Whole Brain Radiation Therapy

CTV Clinical Target Volume

PTV Planning Target Volume

OAR Organ(s) at Risk

NAL No Action Level

TPS Treatment Planning System

CCD Charge-coupled device

TPS Treatment Planning System

QA Quality Assurance

DC Daily Check

DVH Dose Volume Histogram

DOF Degrees Of Freedom

AAPM The American Association of Physicists in Medicine

Contents

1 Introduction

The number of cancer patients in Sweden is increasing. Each year, about 60 000 people are diagnosed. The Swedish Cancer Society estimates that in about 20 years, 100 000 new cases will be detected per year [2]. However, thanks to the development of new diagnostic methods and treatment techniques, the risk of dying in cancer is gradually decreasing.

Brain metastases is the most frequent intracranial malignancy and occur in 20% to 40% of adults with systemic cancer [3]. Brain metastases most often arise from primary tumors that originate from lung, breast or malignant melanoma, have an overall poor prognosis and significantly contribute to cancer morbidity and mortality [4]. Patients with brain metastases are most often treated with surgery, radiotherapy or a combination of these two modalities.

During the last decades, radiotherapy has evolved, with the introduction of new advanced techniques and computerized accelerators. In radiotherapy, the radiation can be delivered to the tumor with high precision. To ensure patient position before treatment, image-verification is nowadays often performed on-line, while the patient is on the treatment couch. New techniques such as volumetric modulated arc radiotherapy (VMAT) and advanced adaptive radiotherapy have led to treatments with increased conformity and steeper dose gradients. Today, brain metastases are often treated with stereotactic radiotherapy (SRT), which implies a high fraction dose delivered to a small target volume. Such precise treatment techniques requires accurate and reproducible patient positioning for multi-fractional irradiations. Small errors in patient or tumor position may have large dosimetric effect, and thereby a negative impact on treatment effect.

To ensure accurate patient positioning, different immobilization equipments are used. For SRT patients, the conventional immobilization device is a custom-made full-head thermoplastic mask in combination with a standard head support. The mask should be capable of limiting intra- and interfractional motions as well as preserving the patients shape from treatment planning. However, patient set-up cannot always be perfectly reproduced for all treatment fractions [5]. This error in positioning can currently only be detected with on-line image verification of the patient position. Furthermore, many patients find the masks uncomfortable and claustrophobic [6].

On-board imaging techniques can only verify the patient position prior to the treatment, meaning that there is a risk for patient movement within the mask after image-verification, without it being observed or corrected for. Thus, there is a clinical demand to implement a more practical alternative to the closed masks to increase patient comfort, while maintaining an effective treatment with accurate positioning and improved monitoring of the patient position. In recent years, optical surface scanning (OSS) has been implemented in radiotherapy with the intention of reducing set-up errors and intrafractional motions, without the use of ionizing radiation. Numerous studies have found that the OSS systems have great potential as a clinical complement to on-board imaging techniques, for radiotherapy patients with different diagnoses [7] [8] [9].

At the radiotherapy department at Skåne University Hospital in Lund (in this thesis referred to as the clinic) the OSS system Catalyst™ (C-RAD positioning AB, Uppsala, Sweden) has been implemented. The system calculates the geometrical shifts from a reference surface (generally extracted from the planning Computed Tomography (CT)) to the patient's live surface using an non-rigid algorithm. The OSS system also provides a real time monitoring function to detect patient movement during treatment. Furthermore, the system has the potential to verify the patient position on-line, for every couch angle. Today, for advanced radiotherapy treatments with various couch angles, the treatment position is only verified with the couch in 0°. After verification and correction of patient position, it is assumed that the patient is accurately re-positioned for the following couch angles.

For conventional closed, full-head masks, the use of OSS is limited by the mask blocking the patient's facial area. The OSS system will mainly display the position of the mask and not the patient. An alternative to the closed masks are open-face masks. With open-face masks in combination with an OSS system, the geometrical shifts during positioning and treatment can be monitored and quantified. In addition, open masks are often more comfortable and less claustrophobic. Several studies have presented results for open-face mask solutions, showing good accuracy in patient positioning [10] [11].

Common practice is to position SRT patients with closed, full-head masks using conventional laser based set-up, and to verify the position with Cone-Beam Computed Tomography (CBCT), an on-board imaging technique, at couch angle 0°. To make open-face masks an alternative in radiotherapy for SRT patients, they have to show similar levels of motion control and patient positioning as closed masks. In this thesis a SRT workflow using open-face mask immobilization and an OSS system was investigated in terms of patient positioning.

A recently released algorithm for calculating the isocenter shift with the OSS system, specifically developed for SRT treatments was used for all measurements in this thesis. To the best of our knowledge, this novel algorithm has not been previously clinically evaluated.

1.1 Aim

The aim of this master thesis was to evaluate the novel SRT algorithm for the OSS system, in combination with open-face masks for SRT treatments, and to elucidate any potential improvement in patient positioning.

Set-up accuracy and agreement with current gold standard for patient positioning (CBCT) was evaluated in a phantom study. The study also considered the optical surface scanning system performance for validating treatment position for non-coplanar treatments with various couch angles. With current methods, the treatment position is only verified at couch angle 0°.

An additional aim was to evaluate the dosimetric effect of uncertainties in patient positioning, caused by the couch rotations used for non-coplanar treatments.

2 Theory

2.1 Stereotactic Radiotherapy

Stereotactic radiotherapy (SRT) or Stereotactic radiosurgery (SRS) are types of radiotherapy treatments that deliver a highly precise radiation dose to a well defined target volume. The steep dose gradients achievable with SRT and SRS allow for small target margins. The treatment can be delivered as a single fraction (SRS) or as few multiple fractions (SRT). Due to the complexity of the radiation delivery, the patient positioning accuracy is critical for a satisfying treatment result. Inter- and intrafractional motions can result in insufficient target coverage or increased dose to normal tissue, and thereby a poor treatment outcome.

In a randomized multi-institutional trial, directed by the Radiation Therapy Oncology Group (RTOG), Andrews et al. (2004) assessed the potential benefits of SRS for patients with brain metastases [12]. Of the patients included in the study, 167 of them were treated with whole brain radiation therapy (WBRT) and 164 of them were treated with WBRT followed by a SRS boost. The authors found that WBRT followed by a SRS boost improved complete response, local control rates and the ability to perform usual activities after treatment (Karnofsky Performance Status) for all patients. They also found a significant survival benefit for patients with a single brain metastasis, and therefore suggested this as the standard treatment for patients with a single brain metastasis and to be considered for patients with two or three metastases.

SRS was further investigated by Aoyama et al. (2006), who compared WBRT followed by a SRS boost with SRS only, in terms of mortality and neurological function for patients with limited brain metastases [14]. This randomized trial included 132 patients with brain metastases. Aoyama et al. concluded that SRS only was associated with increased brain tumor recurrence, although it was the authors belief that this was outweighed by the control of systematic cancer. Therefore, SRS only was suggested as a treatment option for patients with limited brain metastases, provided that frequent imaging for brain tumor status was conducted.

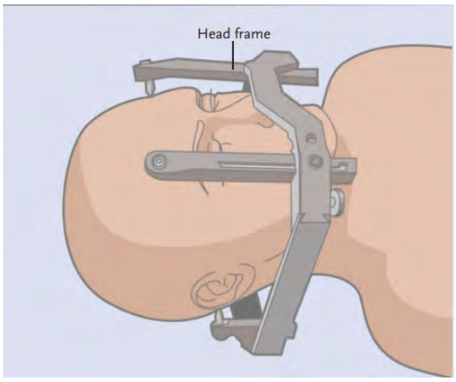


Figure 1: A fixed frame that traditionally has been used for SRT and SRS treatments [13].

Traditionally, SRT and SRS have been executed using a fixed frame fixation device (Figure 1) that is screwed to the patient's head. The frame establishes the target coordinates and ensures accurate patient positioning during treatment. Recently, alternative frameless devices have been implemented to replace the head-frame. The immobilization device that is most often used in the clinic for SRT and SRS is thermoplastic full-head masks (described in section 2.4.1). An alternative treatment technique that is often used for SRS and SRT treatments is the Gamma Knife (Elekta AB, Stockholm, Sweden).

2.2 Set-up deviations in radiotherapy

A requirement for successful radiotherapy treatment is an accurate and reproducible patient set-up. Patient positioning can be verified with numerous methods, including on-board imaging. On-board imaging performs planar or volumetric image acquisition using megavoltage imaging, kilovoltage imaging or CBCT. The current gold standard for verification of set-up for patients with brain metastases is CBCT. It produces images with enough quality to differentiate bone, soft tissue and air cavities.

To compensate for the geometrical set-up and delivery uncertainties in order to ensure target coverage, a margin is added to the clinical target volume (CTV) to form the planning target volume (PTV). These margins should take into account all geometrical variations and inaccuracies. The brain region contains a lot of organs at risk (OAR) with different tolerance doses. An increased planning target volume is associated with increased dose to the surrounding healthy tissue and OARs. This can lead to an increased risk for treatment-related complications for the patient and impaired quality of life [15]. Thus, it is essential to reduce the positioning uncertainties, which will enable the use of smaller margins without compromising target coverage.

At the clinic within this study, SRT patients are currently positioned using conventional laser-based set-up, followed by CBCT imaging, for fine tuning and verification of the position.

2.2.1 Systematic and random set-up deviations

Inaccuracy in position arise from various reasons, including a systematic deviation between patient immobilization at simulation and treatment, random daily set-up errors and changes in the patient's anatomy during the period of treatment.

Random set-up deviations, σ, occur when the position is incorrect due to daily fluctuations. Random deviations are usually reduced by patient immobilization. Systematic set-up deviations, Σ, are due to differences between the planned patient position and the actual position at treatment, such as transfer of errors from simulation to treatment positioning or inaccuracies in the algorithm for calculation of dose distribution. These deviations can lead to a shift of the dose distribution from the planned patient position to a mean patient position. Systematic deviations are usually reduced using a set-up correction strategy. At the clinic within this study the correction strategy used is based on the NAL (No Action Level)-strategy introduced by Boer et al. (2001) [16] in combination with the Adaptive Maximum Likelihood-strategy by Shalev et al. (1995) [17]. The combination was introduced by S. Månsson (2004) [18].

The total set-up deviation is a combination of both systematic set-up deviations and random set-up deviations. These two components are defined as the standard deviations of the individual systematic and random set-up deviations for all patients, respectively, and can only be separated if multiple images are acquired. The higher amount of images that are acquired, the more accurate the estimation will be. Typically, over 20 patients should be analyzed in order to establish an accurate estimation of Σ and σ. In the calculation of Σ and σ they are assumed to be normally distributed. The following formulas was presented by Tony Greener, 2003 [19].

The individual systematic set-up deviation for patient p in a given direction:

$$m_{\mathrm{p}} = \frac{1}{n_{\mathrm{p}}} \sum_{i=1}^{n_{\mathrm{p}}} \mu_{\text{(ref-setup)i}} \tag{1}$$

where n_{p} is the number of images taken for patient p and $\mu_{\text{(ref-setup)}}$ is the deviation between the set-up image relative to the reference image in a given direction.

The individual random set-up deviation for patient p in a given direction:

$$\sigma_{\mathrm{p}} = \sqrt{\frac{1}{n_{\mathrm{p}}-1} \sum_{t=1}^{n_{\mathrm{p}}} (\mu_{\text{(ref-setup)i}} - m_{\mathrm{p}})^2} \tag{2}$$

The overall mean systematic deviation for all patients in the study:

$$m_{\mathrm{o}} = \frac{1}{N} \sum_{p=1}^{P} n_{\mathrm{p}} \cdot m_{\mathrm{p}} \tag{3}$$

where N is the total number of images included in the study and P is the total number of patients for which images were acquired.

The systematic set-up error for a patient population:

$$\Sigma = \sqrt{\frac{P}{N(P-1)} \sum_{p=1}^{P} n_{\mathrm{p}} (m_{\mathrm{p}} - m_{\mathrm{o}})^2} \tag{4}$$

The random set-up error for a patient population:

$$\sigma = \sqrt{\frac{1}{N-P} \sum_{p=1}^{P} \sigma_{\mathrm{p}}^2 (n_{\text{p-1}})} \tag{5}$$

Apart from set-up errors, intrafractional motions such as organ motions, breathing and swallowing motions also has to be considered when calculating the required treatment margins.

2.3 Optical surface scanning

Optical surface scanning is becoming more widely used for monitoring and quantifying patient set-up and intrafractional motion during treatment. OSS is non-invasive and do not expose the patient to ionizing radiation. The Catalyst™ system used in this master thesis (Figure 2) is provided by C-RAD Positioning AB (Uppsala, Sweden).

The OSS system uses LED to project a near-visual light onto the patient and a charge-coupled device (CCD) camera to detect the light reflected from the patient. Using the information from the reflection the system generates a live 3D surface of the patient, which is then compared to a reference surface for verification. The reference surface can for instance be the external body contour from the planning CT scan. The geometrical shifts from the reference surface to the patient's live surface is calculated using a non-rigid algorithm. The 3D surface is reconstructed based on the principle of triangulation and the calculated positions inaccuracy are displayed in real-time in six dimensions, including translational shifts (vertical, longitudinal and lateral) and rotational shifts (rot, pitch and roll).

Figure 2: The Catalyst™ system provided by C-RAD Positioning AB.

To facilitate the set-up process the system uses light of three wavelengths; blue (λ=405 nm), green (λ=528 nm) and red (λ=624 nm). The blue light is the measuring light projected on the patient to determine the skin surface coordinates. The green and red light projects mismatches of the reference surface versus the live patient surface directly onto the patient skin. The OSS system aims to increase patient positioning accuracy and enables live monitoring of the patient.

The OSS system also provides a real time monitoring function to detect patient movement during treatment, as opposed to CBCT where the patient position can only be verified at the time when the image is acquired, i.e. there is a risk of patient movement within the mask after CBCT verification. If the patient moves outside the tolerance level during treatment the radiotherapist can restore the patient to the correct position with support from the OSS system and continue the irradiation without additional image-verification. For SRT, surface scanning may increase patient comfort by reducing the need of immobilization.

The OSS system also has the ability to validate the patient position on-line for all couch angles. Thus, it has the ability to verify couch movements for non-coplanar treatments and to monitor patient position during the couch movement.

The OSS system include a main camera unit which can be extended with two additional camera units with 120 degrees angle from the main unit, in order to get optimal coverage of the patient. Patient data is imported to the OSS system from the Treatment Planning System (TPS). The reference surface can either be the patient surface structure from the CT-scan or be created directly in the OSS system at the time of treatment delivery. In the settings-mode, different settings such as scan volume and camera settings can be adjusted. For SRS treatments the scan volume should be adjusted to only include the opening of the mask. The camera settings include exposure time and saturation (gain), which can be altered to optimize the quality of the live surface. For SRT treatments the camera settings should be equal for all three cameras. The OSS system can be operated in three different modes; positioning, monitoring and respiration. The respiration mode is an application for monitoring patient breathing and will not be further discussed in this thesis. After collection, the data can be evaluated retrospectively (off-line) in the software. The positioning result between the live surface and the reference surface will be displayed as a distance map and as calculated values.

2.3.1 Algorithm

Currently, the OSS system in the clinic is using a non-rigid algorithm to calculate the isocenter shift due to patient set-up or movement. This algorithm utilizes a non-rigid registration of the object to handle object motions during the scan. However, for SRT/SRS treatments the thermoplastic mask controls the position of the head and thus do not introduce movements to as high extent as other patient groups (for example breast patients) may. A novel algorithm for SRS/SRT treatments has been developed by the OSS system vendor to provide higher accuracy for patient positioning using the OSS system. The novel algorithm uses the non-rigid registration although with a higher demand set on rigidity. The non-rigid part of the registration is useful to handle blinking eyes etcetera.

A lot of previous research have been focusing on registration of rigid objects [20], but these methods are not applicable on objects that undergo deformations during the scan. The principle behind the non-rigid algorithm used by the vendor has previously been described by Hao Li et al. (2008) [21].

The challenge lies in the registration of two partial scans of a deformable object; a reference scan and a live scan captured at different points in time. To obtain perfect patient positioning these two scans must match. The correspondences are expressed at points distributed evenly over the reference surface so that each point has a corresponding position on the live surface. To register non-rigid objects, both correspondence between the two surfaces and a suitable warping function that matches the deformation of the initial source have to be estimated [21].

The OSS system's calculation of the isocenter shift can be divided into two main steps; 1) aligning the reference surface to the live surface using a registration algorithm and 2) using the registration result to predict the impact on the live surface position by utilizing a volumetric deformable model [9]. The alignment between the reference surface to the live surface is achieved by using a deformable node graph for the source scan. First optical triangulation is used to create 3D triangle meshes for both the reference surface (source mesh) and live surface (target mesh). The deformable graph node is chosen by sampling the nodes of the source scan [21]. The

OSS system use two node graphs, one with a smaller and one with a larger distance between the nodes [9].

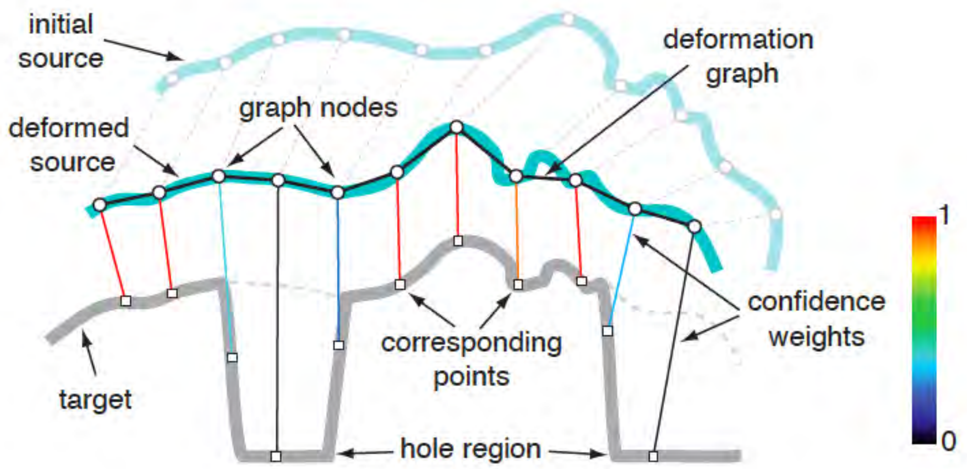


Figure 3: An illustration of the relation between the initial source scan, the deformed source and the target scan. The color of the confidence weights describe the correspondence between the deformation graph node and the target node [21].

Every node in the deformation graph is assigned an "energy" and the sum of the deformation node "energy" represent the global "energy" of the system. The "energy" of the system is defined as a combination of weighted parameters in every deformation node, such as similarity with the connecting nodes and distance to the corresponding point and to the target surface [9].

A non-linear optimization is applied to the deformation node graph to calculate the deformation of the scan and thus find a deformed source that matches the target scan. Each node in the deformation graph should have a corresponding position on the target mesh (Figure 3). Corresponding points between the source mesh and the target mesh are detected by identifying overlapping points between the meshes and removing poor corresponding points. In the optimization process these corresponding positions on the target shape is subsequently updated.

There might be regions in the source scan that do not have corresponding points in the target scan. Instead of considering these as empty regions each pixel is automatically replaced by deep holes (values twice the maximum depth measured in the scan). This way each node in the source mesh is forced to have a corresponding point in the target mesh. In the hole regions the confidence weights are put to zero indicating that no appropriate correspondence is detected. This way the absence of corresponding points do not affect the deformation. Without this modification, regions with no corresponding points would result in many artifacts in the deformation and reduce the accuracy of the isocenter calculation.

The non-linear optimization is a iterative process, with a purpose to find the lowest "energy state" of the system [21]. When the system has reached its lowest "energy state", the deformation of the source matches the target scan and the information can be used to determine the isocenter position. In this step a volumetric mesh consisting of uniformly distributed tetrahedrons is created. The nodes of the volumetric mesh are related to the nodes in the source mesh. Translation and rotation in each node of the volumetric mesh are calculated, based on the source mesh deformation and the target position, to determine the isocenter position [9].

2.3.2 System calibration

The OSS system used in this thesis requires a Routine Quality Assurance (QA) to be performed prior to SRT/SRS treatments. The calibration is valid for four hours, thereafter SRT/SRS treatments cannot proceed and a new Routine QA must be performed. The Routine QA requires a Daily Check (DC) phantom provided by the vendors and a QUASAR™ Penta-Guide Phantom (Figure 4).

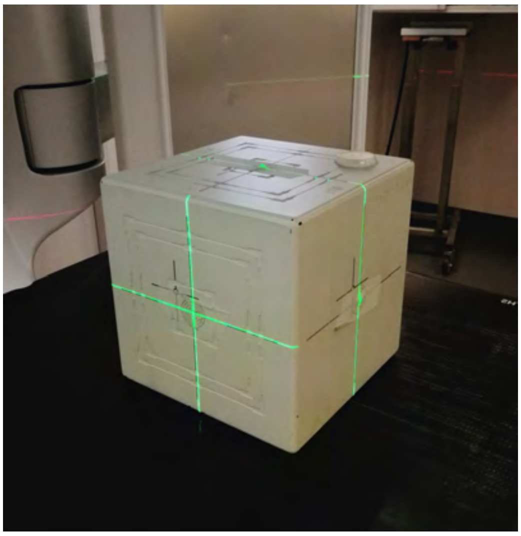


Figure 4: The QUASAR™ Penta-Guide Phantom used for the Routine QA.

The DC device is aligned to the room isocenter using the room lasers and scanned by the OSS system five times to ensure high accuracy. The DC is performed for all three cameras at the same time. The system hardware drift since the previous DC/Routine QA and the total drift since the last isocenter adjustment are shown in the software. If the deviations are within tolerance the information ”Daily Check OK” is displayed and if they are outside the tolerance the information ”Daily Check Outside Tolerance” is displayed highlighted in red. The purpose of the DC is to direct the focus of all three cameras to the same point in space, i.e. the isocenter.

To further adjust the OSS coordinate system to the treatment isocenter the QUASAR™ Penta-Guide Phantom is used. This requires the DC to be completed. The phantom is aligned to the treatment isocenter using CBCT-imaging followed by a couch correction based on the matching result. The phantom is then scanned by the OSS system and the software will display the deviation between the alignment to the room lasers, from the previous step with the DC phantom, and the alignment to the isocenter according to the surface scanning of the QUASAR Penta-Guide Phantom. The user can press ”Add kV or MV couch correction” to compensate the acquired images according to the final CBCT results. It is recommended that the QA of the CBCT-imaging system is performed before Routine QA of the OSS system.

2.3.3 Patient positioning

In the patient positioning mode the live surface is displayed on the OSS screen together with the reference surface (Figures 5 and 6). The OSS system suggests what adjustments to make in order to align the live surface and the reference surface.

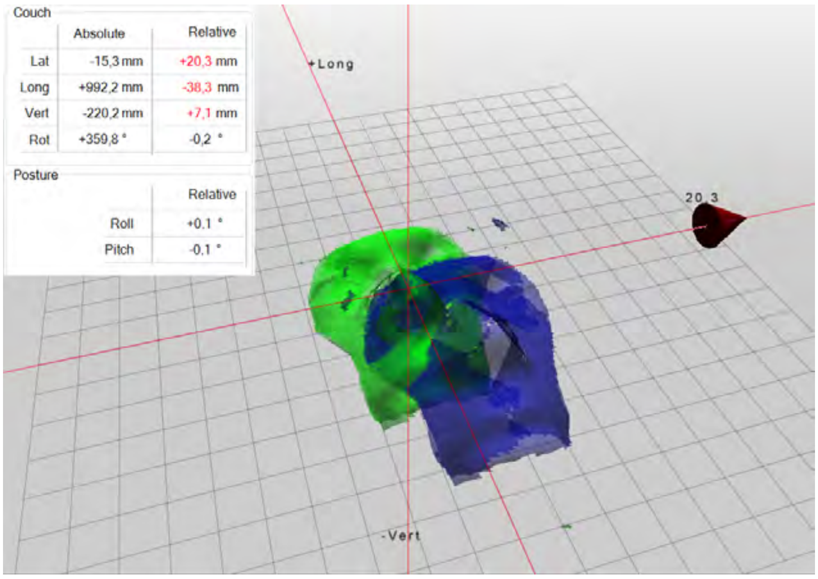


Figure 5: The live surface (green) and the reference surface (blue) displayed on the OSS software and the suggested shifts for a correct patient position.

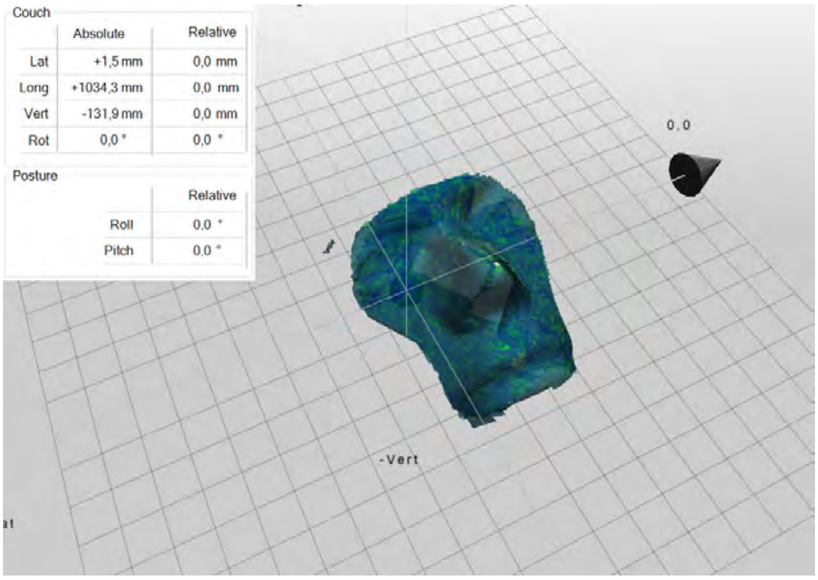


Figure 6: The live surface and the reference surface in perfect alignment, indicating a correct patient position.

In this mode two tolerance levels can be set; target tolerance and surface tolerance. The target tolerance determines how large the accepted difference is between the isocenter calculated from the live surface and the reference isocenter. The isocenter shift is calculated and displayed as numbers on the monitor. If the target tolerance level is exceeded, the numbers are displayed in red. The surface tolerance determines how large the accepted difference is between the live surface and the reference surface at any part of the body. The alignment between the two surfaces are displayed as a color map on the patient's body. Body parts that are positioned to low relative the reference surface are displayed in green (λ = 528 nm) and body parts that are positioned to high are displayed in red (λ = 624 nm). If the live surface and the reference surface are aligned within the set tolerance level the surface will be displayed in transparent color. The color map can also detect rotations in the patients position.

2.3.4 Real time monitoring

In the monitoring mode the live surface from the patient positioning mode after any positioning adjustments is used as a reference surface for that day's monitoring. During treatment, the OSS system monitor patient movement relative to the reference surface and calculates deviations between the calculated isocenter (from the live surface) and the planned isocenter (from the reference surface).

The OSS system suggests which adjustments to make in order to align the live surface and the reference surface. The total isocenter shift (a vector combining the deviations in the vertical, longitudinal and lateral direction) is continuously updated and displayed as bars in a diagram. When the shift is within tolerance the bars are displayed green and when the tolerance level are exceeded the bars become red.

For treatment plans that acquire couch rotations, like SRS, the patient can also be monitored. When loading a treatment field with couch rotations to the accelerator, the reference surface will rotate relative to the OSS isocenter. However, if the OSS isocenter is not in perfect alignment with the treatment isocenter, the misalignment can introduce falsely OSS-indicated displacements when couch rotations are performed.

It is possible to pre-set an automatic beam interruption whenever the tolerance level is exceeded. This way the patient will never be irradiated outside the tolerance area in case of patient movements.

2.4 Immobilization

In radiotherapy, immobilization is critical to obtain an accurate patient positioning and to prevent movement during treatment. Therefore, it is an important factor for safe and reproducible delivery of the treatment. Brain metastases patients are usually immobilized with custom-molded thermoplastic head masks. The most widely used immobilization for brain metastases patients are closed, full-head masks (Figure 7a). These masks have been found to result in an accurate reproduction of patient positioning and are well characterized in terms of head motion within the mask and thereby allows calculation of the treatment margins required [6]. However, the use of the closed full-head masks are uncomfortable for most patients and even intolerable for some, especially for patients suffering from claustrophobia.

In this thesis an alternative to the closed, full-head mask is being evaluated in terms of patient positioning. The three-point open-face mask (Figure 7b) leaves eyes, nose and mouth exposed and have reinforced strips around the openings and locking edges. Apart from increased accuracy in patient positioning, the open-face mask also aims to reduce the feeling of claustrophobia during treatment. It is expected that people suffering from claustrophobia, and therefore can not go through treatment with conventional closed masks, should be able to go through with the treatment if these open-face masks were used.

The open-face mask can be used in combination with the OSS system to verify patient positioning at every fraction. It also has the potential to verify patient position at couch angles different from zero, which is not possible with the conventional method of closed masks and CBCT imaging.

a b

Figure 7: Immobilizations for brain treatments. A closed full-head mask (a) and an open-face mask (b), both produced by Orfit Industries, Wijnegem, Belgium.

3 Material and Methods

The thesis was separated into three parts:

- A retrospective study of set-up deviations for SRT patients previously treated at the clinic with conventional closed full-head masks.
- A phantom study where multiple evaluations were carried out using an open mask in combination with the OSS system;
  1) the accuracy of positioning for coplanar treatments,
  2) the agreement between the OSS system and the CBCT system,
  3) the accuracy of positioning for non-coplanar treatments,
  4) the effects of a miscalibration between the linac isocenter and the OSS isocenter.
- An evaluation of the dosimetric effect of patient positioning uncertainties in clinical non-coplanar SRT treatment plans.

3.1 Retrospective study

In the retrospective study, the current patient positioning method used at the clinic was reviewed for 50 SRT patients. The patients included in the study were immobilized with three-point thermoplastic full-head masks (Orfit Industries, Wijnegem, Belgium) and a standard head support. All patients were treated on a TrueBeam™ Radiotherapy System (Varian Medical Systems, Palo Alto, CA). The set-up was based on room lasers and markers and the position was verified by CBCT-imaging to ensure correct patient positioning. All treatments were carried out with coplanar beams. The set-up deviations were collected from Varians Eclipse™ Treatment Planning System in the mode "Offline Review", where the verification CBCT-images had been compared to the planning CT images in an online-match carried out by the radiotherapists while the patient was on the treatment couch. The translational set-up deviations between the laser based set-up and the position verified by CBCT-imaging were collected for 50 SRT patients treated at the clinic between 2015 and 2017, with a total of 166 fractions. The Shapiro-Wilks test with α=0.05 was carried out to determine if the set-up deviations in each direction were normally distributed.

3.2 Phantom study

In the phantom study, the head and neck region of an Alderson RANDO Phantom (Alderson et al. (1962), [1]) was used. The RANDO phantom is transected horizontally into 2.5 cm thick slices and incorporates materials to simulate various tissues, bone, air cavities etc. To make it easier for the OSS system to scan the surface, the RANDO phantom was painted white in the area where the face is exposed (Figure 8a).

The Alderson RANDO Phantom was placed on the couch with a head support while a three-point open-face mask (Orfit Industries, Wijnegem, Belgium) was heated at 69° for 13 minutes. The mask was then molded to fit the shape of the phantom's head and allowed to harden for 10 minutes. These steps are common practice for patients with thermoplastic masks treated at the clinic. After the molding process a reference point was defined in the brain using lead markers and the phantom was simulated on a CT scanner using the standard protocol for stereotactic brain treatments at the clinic (2 mm slice thickness).

a b

Figure 8: The Alderson RANDO Phantom immobilized with an open-face mask (a) and the treatment room with a Varian Truebeam linear accelerator and the ceiling-mounted three-camera OSS system (b).

3.2.1 Positioning at couch angle 0°

For coplanar treatments, the phantom study included measuring the set-up accuracy of the OSS system (with software c4D™ version 5.3.2), in combination with open-face masks, as well as the agreement between the isocenter shift calculated by the OSS system and the isocenter shift suggested after image-verification with CBCT. This was carried out through multiple measurements of $\mu_{(\text{ref-CBCT})}$ (i.e. the deviation between the CBCT verification image relative to the reference image) and $\mu_{(\text{ref-CBCT})}$-$\mu_{(\text{ref-OSS})}$ (i.e. the agreement between CBCT and OSS), in each translational and rotational direction.

A treatment plan was created for the Alderson RANDO phantom, with four PTVs placed at various positions in the phantoms brain (Figure 9); one at the center (purple), one in the cranial direction (yellow), one in the lateral direction (green) and one in the ventral direction (blue). The central PTV (purple) was placed close to the reference point and the other PTVs were placed at a distance of 3.5 cm from the central PTV. A treatment plan was created for each PTV, with the isocenter in the center of the PTV. Before the measuring session, a Routine QA (section 2.3.2) was performed in accordance with the OSS system user guide for the SRT algorithm. After positioning the phantom, using CBCT verification, a new reference surface was acquired from the OSS system before the measurements were started. Acquiring the OSS reference surface after verification of position by CBCT eliminates the intrinsic variances between the two systems. All measurements were performed on a TrueBeam™ Radiotherapy System (Varian Medical Systems, Palo Alto, CA) (Figure 8b).

The following procedure was performed for each isocenter:

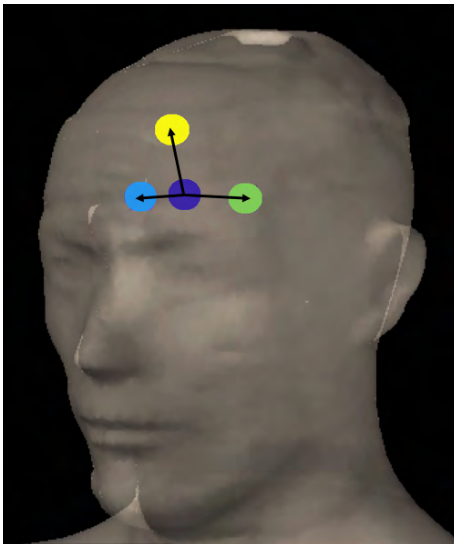


Figure 9: Four PTVs placed in different parts of the brain of the Alderson RANDO phantom.

1. The phantom was immobilized on the treatment couch using the open-face mask (Figure 8b), and aligned to the reference point using the room lasers.
2. The couch was moved to align the calculated isocenter and planned isocenter using the OSS auto-couch function.
3. A CBCT-image was acquired and the $\mu_{\text{(ref-CBCT)}}$ was calculated using the on-line auto-match function. The auto-match was performed both with 3 degrees of freedom (DOF) (translations only) and with 6 degrees of freedom (translations and rotations).
4. The set-up deviation between the live surface from the OSS system relative to the reference surface, $\mu_{\text{(ref-OSS)}}$, was also registered to evaluate the agreement between the set-up deviation suggested after CBCT-verification and the set-up deviation suggested by OSS system ($\mu_{\text{(ref-CBCT)}}$ - $\mu_{\text{(ref-OSS)}}$).

The procedure was reproduced ten times for each PTV. Between each session the mask was removed from the phantom and the couch was reverted to the reference point. The Shapiro-Wilks test (α=0.05) was carried out to individually determine if the set-up deviations in each direction for each of the PTVs were normally distributed. A Kruskal-Wallis test (α=0.05) was carried out with the null hypothesis *"The four PTVs set-up accuracy medians in the vertical/longitudinal/lateral direction are equal"*, to determine differeces in set-up accuracy for different PTV positions.

3.2.2 Positioning for non-coplanar treatments

The phantom study also included an evaluation of the positioning for non-coplanar treatments, i.e. treatments with couch rotations. In this step, the same PTVs and treatment plans were used as in the previous section (3.2.1).

The method can be separated into three steps:

1. A field with a couch angle $\neq 0°$ was loaded on the Truebeam™ system. The OSS mode was changed from the patient positioning mode to the real time monitoring mode and the couch was rotated to the given couch angle. When the couch was in the correct position according to the treatment machine, $\mu_{\text{(ref-OSS)}}$ was registered. This procedure was performed for couch angles 45°, 90°, 270° and 315°, for each of the four PTVs.

2. For couch angles $\neq 0°$, patient position cannot be validated in 3D since a CBCT can only be acquired in 0°. The OSS-indicated offsets evaluated in step 1 was either caused by a misalignment between treatment isocenter and CBCT isocenter, couch rotation offsets, uncertainties in the OSS calculation of the isocenter shift or a combination of these three parameters. To investigate if the OSS system is able to validate patient position for couch angles $\neq 0°$, these three uncertainties need to be isolated. An experiment was performed with the intention of isolating the deviation caused by mechanical limitations in the couch and the deviation caused by uncertainties in the OSS calculation of the isocenter shift. This was carried out by calibrating the OSS isocenter to the treatment isocenter, instead of the CBCT isocenter, using Mega Voltage (MV)-imaging. The Alderson RANDO phantom was positioned on the couch using MV-verification and a steel ball was placed on top of the phantom at the isocenter-point for the longitudinal and lateral directions. MV-images were acquired at couch angles 0°, 45°, 90°, 270° and 315°. In the "Portal Dosimetry" module of Aria® (Varian Medical Systems, Palo Alto, CA), the MV-images for couch angles $\neq 0°$ were evaluated by measuring the offset from the treatment isocenter at couch angle 0°. In this step, the couch rotation offset was identified. The procedure was repeated by correcting the position according to the OSS-indicated values before acquiring the MV-images. Again, the offset from the treatment isocenter was evaluated in "Portal Dosimetry". In this step, the uncertainties in the OSS calculation of the isocenter position for each couch rotation was identified.

3. To evaluate the effect of an improperly calibrated OSS system, the procedure in step 1 was repeated two times with an intentional misalignment between the treatment isocenter and the OSS isocenter. The misalignments were of +3 mm and +1 mm, respectively, in the longitudinal direction. For this set-up, the misalignments were not corrected for when performing the Routine QA.

3.3 Dosimetric effect of patient positioning uncertainties

To evaluate the dosimetric effect of patient positioning uncertainties due to mechanical limitations existing for non-coplanar treatments, the worst-case isocenter shift was applied to ten clinical treatment plans to create uncertainty plans. The protocols were 30 Gy in 3 fractions. However, only four of the 15 PTVs that were evaluated were clinically treated with non-coplanar beams.

Uncertainty plans were created in Varians Eclipse™ TPS in the mode "External Beam Planning". In the function "Plan Uncertainty Parameters" the worst-case isocenter shift were entered for 1) todays common practice for SRT treatments without the use of an OSS system and 2) a workflow using an OSS system to correct for couch offsets. The TPS generated and calculated uncertainty plans with shifts in each translational direction (±vertical, ±lateral, ±longitudinal), respectively.

The worst-case isocenter shifts were calculated as follows:

1) **Without OSS system**. The tolerance for CBCT isocenter and treatment isocenter alignment used at the clinic is 1 mm. In addition, the tolerance for couch offset from the treatment isocenter is 2 mm in the longitudinal or lateral direction. Thus, the worst-case scenario in todays common practice, without use of the OSS system, would be a CBCT isocenter drift of 1 mm from the treatment isocenter at couch angle 0° and a couch rotation offset of 2 mm from the treatment isocenter. As the couch rotates, the misalignment between the CBCT isocenter and the treatment isocenter in the longitudinal or lateral direction will increase. Based on geometry, the misalignment in 0° would cause the displacement at ±90° couch rotation to be equal to $\sqrt{2}$ * the magnitude of the misalignment [22]. Therefore, the worst-case scenario for todays common practice for non-coplanar SRT treatments without the use of the OSS-system, is that the patient position is 3.4 mm off from the treatment isocenter (2 mm couch offset plus 1.4 mm displacement between patient position and treatment isocenter) when rotating the couch to ±90°.

2) **With OSS system**. With the OSS system integrated, the system is expected to identify the couch offset and suggest a correction. In the couch offset correction, the maximal uncertainty in the OSS system calculation of the isocenter shift at couch angles $\neq 0°$ found in the previous experiment in section 3.2.2 was used. Since the OSS system is calibrated to align with the CBCT system, the OSS will not identify the misalignment between the CBCT isocenter and the treatment isocenter. Thus, for a workflow using the OSS system to compensate for the incorrect couch calibration, the worst-case scenario is that the patient position is 1.9 mm off from the treatment isocenter (1.4 mm displacement between patient position and treatment isocenter plus 0.5 mm uncertainty in the OSS system calculation of the isocenter shift) when rotating the couch to ±90°.

The volume of PTV receiving 95% of the prescribed dose, V(95%), was collected from the Dose Volume Histogram (DVH) of the original plans as well as the uncertainty plans in order to evaluate the impact of the isocenter shifts on PTV coverage (Figure 10).

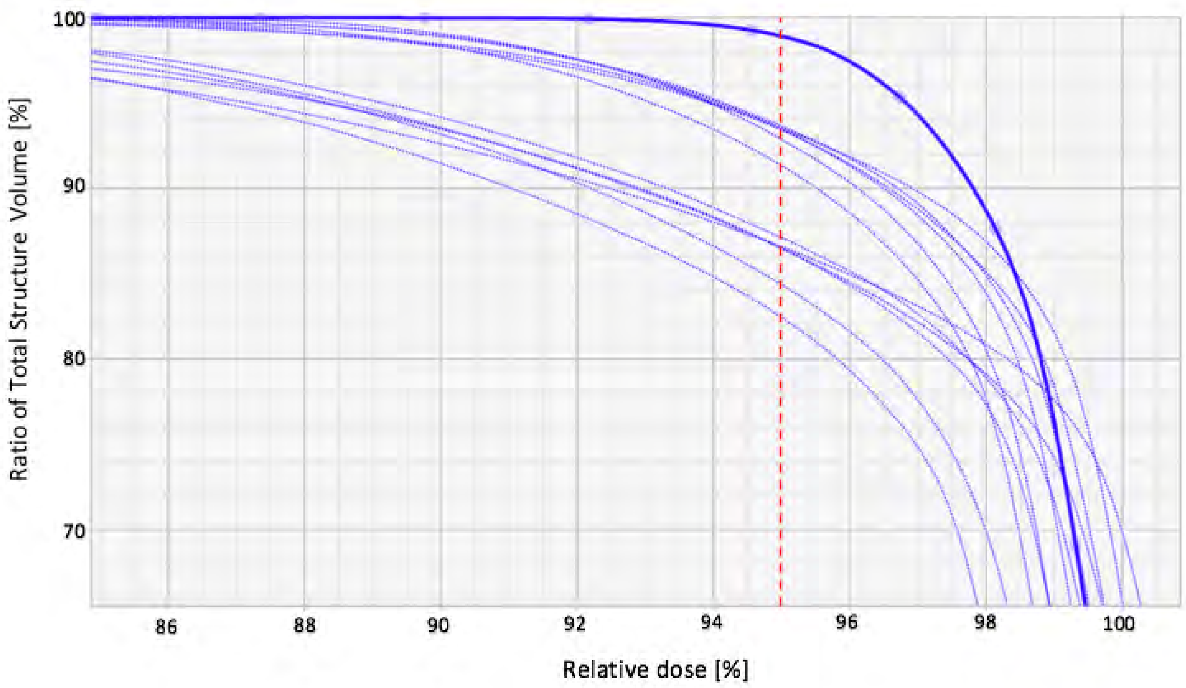
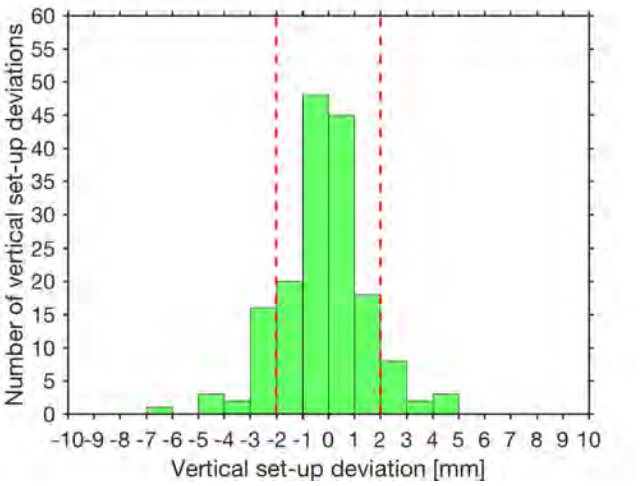


Figure 10: DVH for one of the PTVs used to evaluate the dosimetric effect of an isocenter shift. The DVH includes the original plan (solid line) and the uncertainty plans (dashed lines). The red line represents the V(95%) value.

4 Results and Discussion

4.1 Retrospective study

The set-up deviations collected from the TPS at the clinic (Eclipse) show that it is rare with deviations outside of the 2 mm action level used at the clinic, but that deviations up to 8 mm exist (Figure 11).



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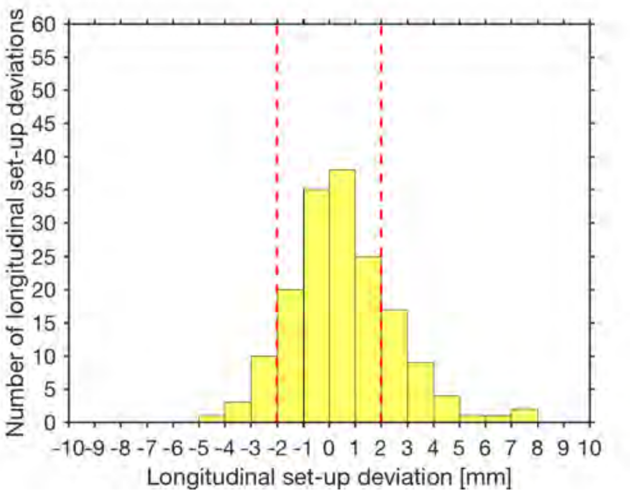

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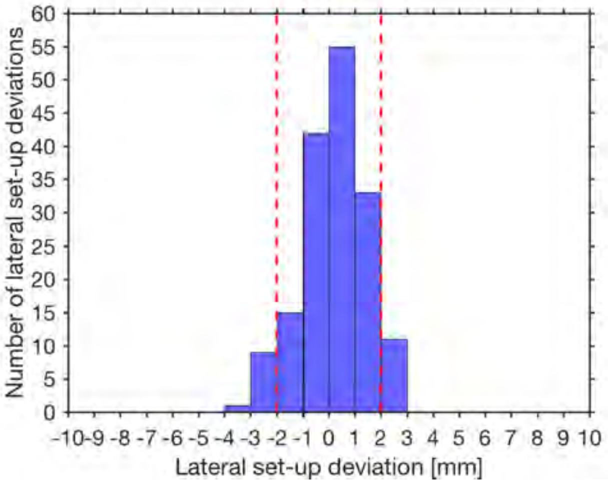

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Figure 11: Set-up deviations collected from the TPS for the 50 SRT patients in the vertical (a), longitudinal (b) and lateral (c) directions. The red dashed lines indicate the action level of 2 mm used at the clinic.

The Shapiro-Wilks test of normality showed that the null hypothesis was rejected in the vertical and longitudinal (p=0.008 and p=0.003, respectively) directions, but not in the lateral direction (p=0.378). That means that the distribution of the set-up deviations can be assumed to be normally distributed in the lateral direction, but not in the vertical and longitudinal direction. This result indicate that the distribution in the vertical and longitudinal direction is not completely random, but do also include a systematic component. The systematic component may for example originate from inaccurate positions of the room lasers or from drift of the CBCT system relative to the accelerator.

The median set-up deviation was -0.2 mm (range -6.1 to 5.0 mm) in the vertical direction, 0.2 mm (range -4.3 to 7.5 mm) in the longitudinal direction and 0.3 mm (range -3.7 to 2.9 mm) in the lateral direction. The largest deviations were found in the longitudinal direction.

The 2 mm action level is within the PTV margins of 3 mm used at the clinic for SRT treatments. However, with improved accuracy in patient positioning there are potential to decrease the dose to the surrounding healthy tissue and thus decrease the risk for treatment-related complications for the patient. To evaluate if the OSS system can be used to improve the patient positioning for SRT patients, a patient study with open-face masks must be performed.

Note that even though all patients within this retrospective study were positioned $\leq$ 2 mm from treatment isocenter, this is only verified at couch angle 0°. If the treatment includes couch angles $\neq$ 0°, it is today only assumed that the deviation from treatment isocenter is the same as in 0°. Furthermore, the current workflow with closed full-head masks do not allow patient real time monitoring during treatment and thus intra-fractional motions cannot be detected. Implementation of the OSS system and open-face masks will provide live monitoring of the patient and if the patient moves outside the tolerance level the irradiation can be interrupted.

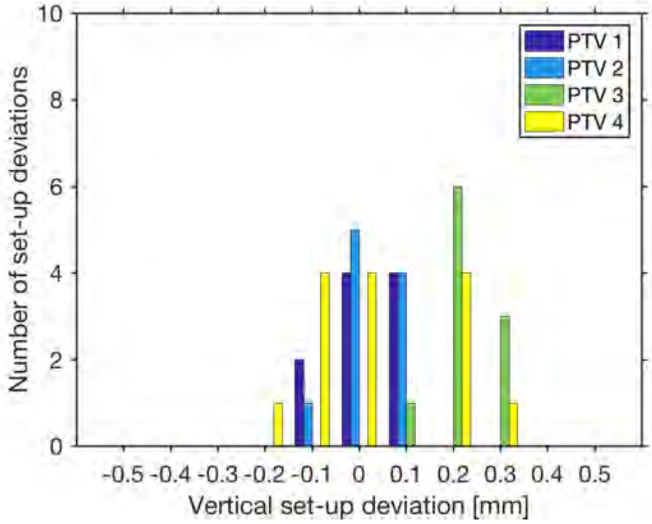
4.2 Positioning at couch angle 0°

4.2.1 Set-up accuracy

The set-up deviation ($\mu_{\text{ref-CBCT}}$) measured when performing 6 degrees of freedom (the translational directions (vertical, longitudinal and lateral) and the rotational directions (rot, roll and pitch)) auto-match between the CBCT verification image and the planning CT image after positioning the phantom with the OSS system were small, $\leq$ 0.5 mm (Table 1, Figures 12 and 13). The result from the Shapiro-Wilks test showed that the set-up deviations were not normally distributed in any direction (Figures 12 and 13).

Table 1: Set-up deviations (6 DOF) with an OSS-based set-up at couch angle 0°.

	Vrt [mm]	Long [mm]	Lat [mm]	Rot [°]	Roll [°]	Pitch [°]
Median	0.1	-0.3	0.0	0.1	0.0	0.2
Range	-0.2 - 0.3	-0.5 - 0.0	-0.3 - 0.3	-1.2 - 1.4	-0.2 - 0.3	0.0 - 0.4



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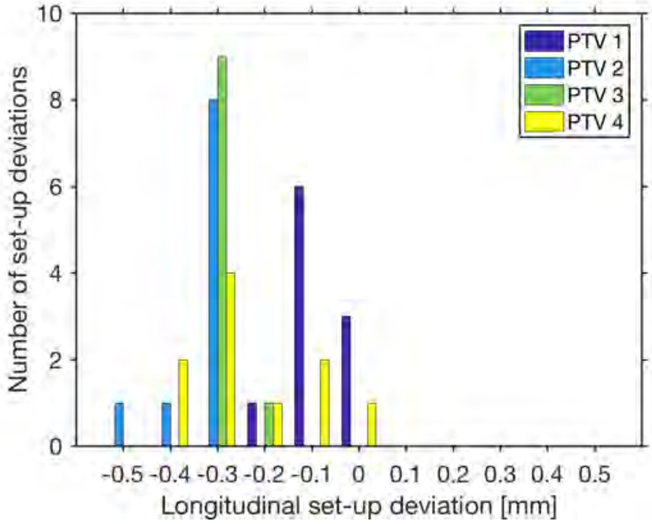

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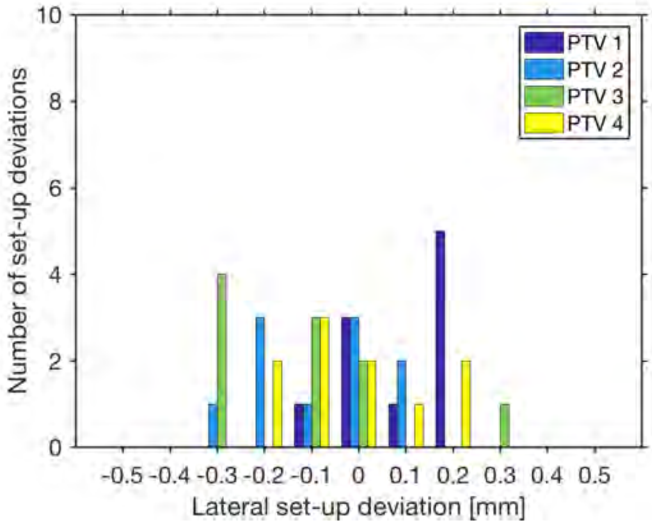

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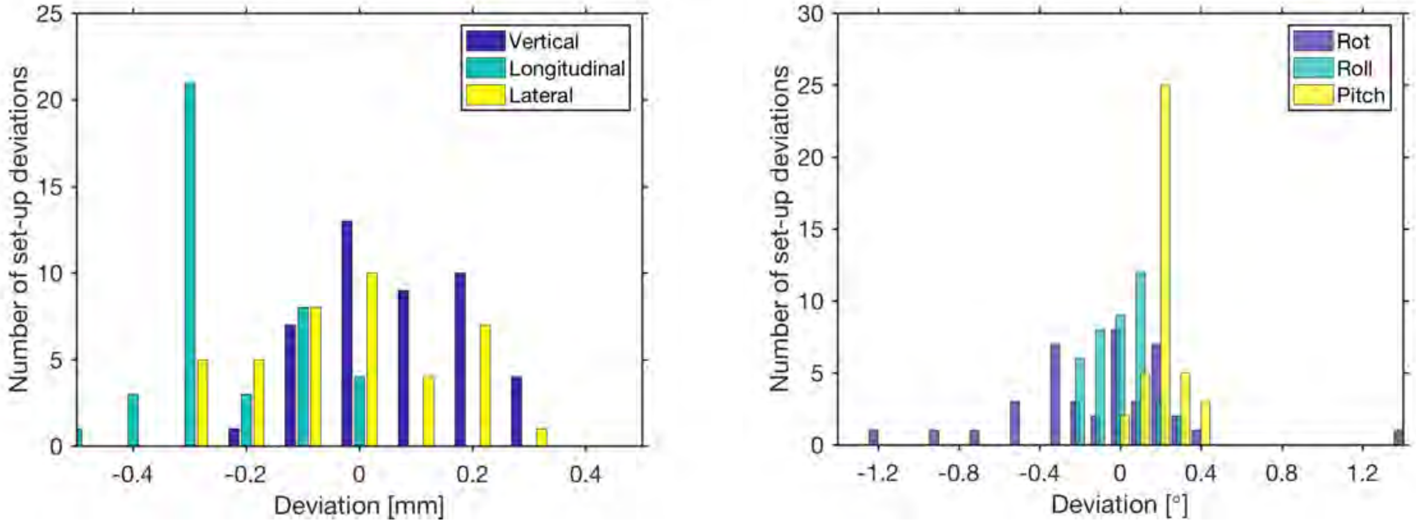
Figure 12: Vertical (a), longitudinal (b) and lateral (c) set-up deviations with an OSS-based set-up at couch angle 0°.



a b

Figure 13: Total translational (a) and rotational (b) set-up deviations for all four PTVs (with different isocent positions), with an OSS-based set-up at couch angle 0°.

The set-up deviation suggested by CBCT imaging after positioning the phantom with the OSS system was within 0.5 mm in all translational directions and within 0.3 mm for 90% of the measurements. The rotational set-up deviations were within 0.4° in the roll and pitch directions, although in the rot direction the values ranged from -1.2 to 1.4°. Note that the auto-couch function was not used for the rotational directions and was difficult to manually adjust. This is demonstrated in the results for set-up accuracy in the rotational direction (Table 1). However, 95% of the measurements showed a displacement of less than 1° in the rot direction. PTV 1 and 2 had the smallest vertical deviations. The smallest longitudinal deviation was found in PTV 1. Overall, the longitudinal direction had the largest deviations, especially for PTV 2. PTV 3 had large deviations in the vertical as well as the lateral direction.

The Kruskal-Wallis test indicated that there was a statistically significant difference in the median set-up accuracy between the four PTVs (p=0.001). The set-up accuracies differed at submillimeter level (Figure 12). With such small differences, it is difficult to assess weather the discrepancy is due to the calculation of the algorithm or other factors.

The individual systematic set-up deviations (m_{p}) and individual random set-up deviations (σ_{p}) were evaluated for each PTV after set-up using the OSS system (Tables 2 and 3). Worth noting is the individual systematic deviation in the longitudinal direction, which ranged from -0.1 mm to -0.3 mm. This might be due to a misalignment between the OSS system and the CBCT system in the longitudinal direction due to uncertainties in the Routine QA. The individual systematic deviations were not further investigated. The overall mean systematic set-up error (m_{o}), the systematic error (Σ) and the random error (σ) were also evaluated (Table 4). The deviations were small and within the action level for SRT treatments.

Table 2: Individual systematic set-up deviation for each PTV in a given direction.

	Individual systematic deviation		
	Vrt [mm]	Long [mm]	Lat [mm]
$m_{\mathbf{p,\ PTV\ 1}}$	0.0	-0.1	0.1
$m_{\mathbf{p,\ PTV\ 2}}$	0.0	-0.3	-0.1
$m_{\mathbf{p,\ PTV\ 3}}$	0.2	-0.3	-0.1
$m_{\mathbf{p,\ PTV\ 4}}$	0.1	-0.2	-0.0

Table 3: Individual random set-up deviation for each PTV in a given direction.

	Individual random deviation		
	Vrt [mm]	Long [mm]	Lat [mm]
$\sigma_{\mathbf{p,\ PTV\ 1}}$	0.1	0.1	0.1
$\sigma_{\mathbf{p,\ PTV\ 2}}$	0.1	0.1	0.1
$\sigma_{\mathbf{p,\ PTV\ 3}}$	0.1	0.0	0.2
$\sigma_{\mathbf{p,\ PTV\ 4}}$	0.2	0.1	0.2

Table 4: Overall mean systematic set-up error, systematic set-up error and random set-up error.

	Overall mean systematic deviation, m_o	**Systematic error, Σ**	**Random error, σ**
Vrt [mm]	0.1	0.1	0.1
Long [mm]	-0.2	0.1	0.1
Lat [mm]	-0.0	0.1	0.2

The results demonstrate that the OSS system provide accurate and reproducible set-up for a phantom at a couch angle of 0°. Further studies has to be performed to investigate the OSS system as a set-up tool for SRT patients. Similar to previous studies [6][7][8], this study found that the OSS system in combination with the open-face masks has great potential as a clinical complement to on-board imaging techniques also for SRT patients. The study gives an indication that an implementation of the OSS system for SRT treatments would provide the similar levels of patient positioning as closed masks.

With only three DOF (translational only), the median set-up deviations was zero in the vertical and lateral direction and -0.1 mm in the longitudinal direction (Table 5). The range of the set-up deviations was -0.3 to 2 mm, -0.3 to 0.3 mm and -0.5 to 0.9 mm in the vertical, longitudinal and lateral directions, respectively (Table 5). It is interesting to note the difference in the shift suggested by the CBCT when performing the auto-match with 6 DOF versus 3 DOF. The Truebeam™ treatment couches within this study only provide couch movements in the translational directions. Thus the isocenter shift calculations and couch movements are based on a 3 DOF match, and compensate for any rotational displacement with a translational correction. The results (Table 5) show that the CBCT suggest a larger movement in the lateral direction when matching with 3 DOF rather than with 6 DOF. To further increase the set-up accuracy using the OSS system, couches with 6 DOF would be preferable.

Table 5: Set-up deviations (3 DOF) with an OSS-based set-up at couch angle 0°.

	Vrt [mm]	Long [mm]	Lat [mm]
Median	0.0	-0.1	0.0
Range	-0.3 - 0.2	-0.3 - 0.3	-0.5 - 0.9

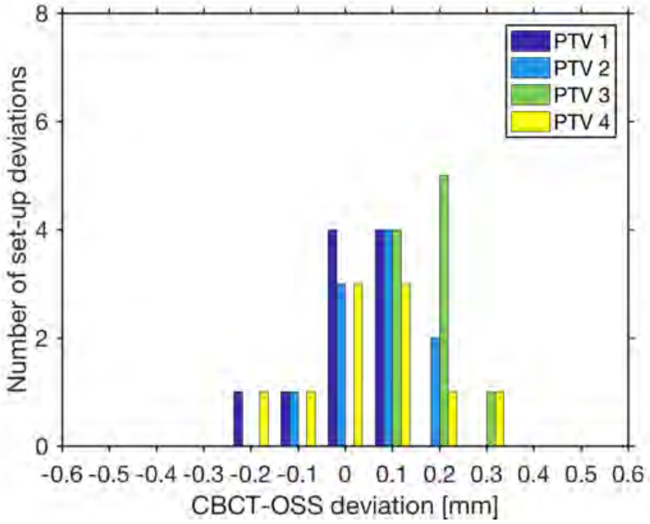
4.2.2 OSS-CBCT agreement

Due to the limitation of the couch movement within this study, the live position was not always in perfect alignment with the reference surface, even after using the OSS system auto-couch function. After set-up, the OSS system indicated that translational shifts were within 0.1 mm in each direction. In the rotational directions the OSS-indicated shifts ranged from -0.9 to 1.4° in the rot direction and from -0.5 to 0.3° in the roll direction after performing the auto-couch. In the pitch direction the maximum deviation was 0.1°. The set-up errors detected by CBCT were retrospectively compared with those indicated by the surface scanning system.

The agreement between $\mu_{(\text{ref-CBCT})}$ and $\mu_{(\text{ref-OSS})}$, when performing auto-match with six DOF, show that the CBCT system and the OSS system were in agreement within 0.5 mm in all translational directions (Table 6, Figure 14 and Figure 15). The median deviation was 0.1, -0.2 and 0 mm in the vertical, longitudinal and lateral direction, respectively. The largest translational deviation was found in the longitudinal direction. For all rotational directions, the CBCT system and the OSS system were in agreement within 0.9°. The median deviation was 0, -0.1 and 0.2° in the rot, roll and pitch direction respectively. The largest rotational deviation was found in the rot direction. As for the set-up accuracy, there was a systematic deviation in the longitudinal direction for the OSS-CBCT agreement. The agreement between $\mu_{(\text{ref-CBCT})}$ and $\mu_{(\text{ref-OSS})}$, when performing auto-match with six DOF, show that the CBCT system and the OSS system were in agreement within 0.5 mm in all translational directions (Table 6, Figure 14 and Figure 15). The median deviation was 0.1, -0.2 and 0 mm in the vertical, longitudinal and lateral direction, respectively. The largest translational deviation was found in the longitudinal direction. For all rotational directions, the CBCT system and the OSS system were in agreement within 0.9°. The median deviation was 0, -0.1 and 0.2° in the rot, roll and pitch direction respectively. The largest rotational deviation was found in the rot direction. As for the set-up accuracy, there was a systematic deviation in the longitudinal direction for the OSS-CBCT agreement.

Table 6: Agreement between $\mu_{(\text{ref-CBCT})}$ and $\mu_{(\text{ref-OSS})}$.

	Vrt [mm]	Long [mm]	Lat [mm]	Rot [°]	Roll [°]	Pitch [°]
Median	0.1	-0.2	0.0	0.0	-0.1	0.2
Range	-0.2 - 0.3	-0.5 - 0.1	-0.3 - 0.2	-0.9 - 0.7	-0.3 - 0.6	0 - 0.4



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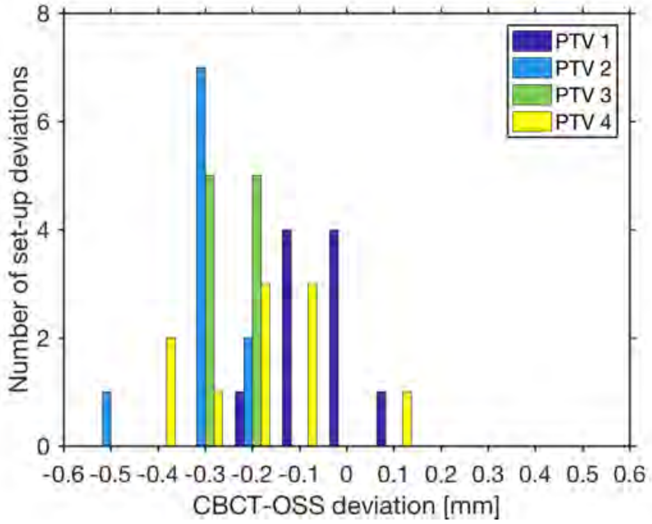

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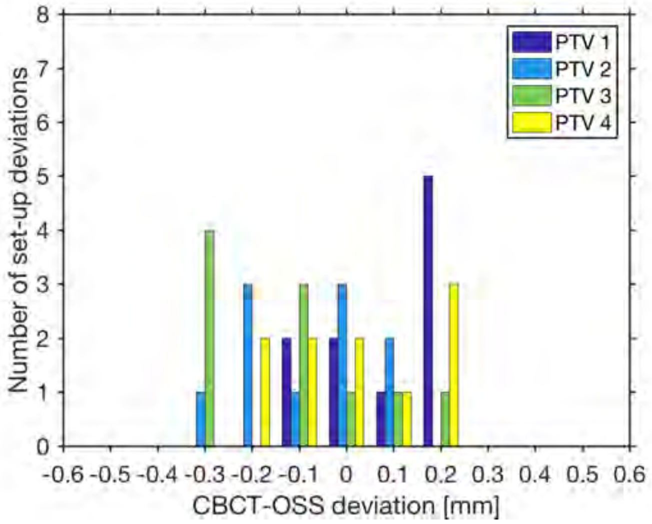

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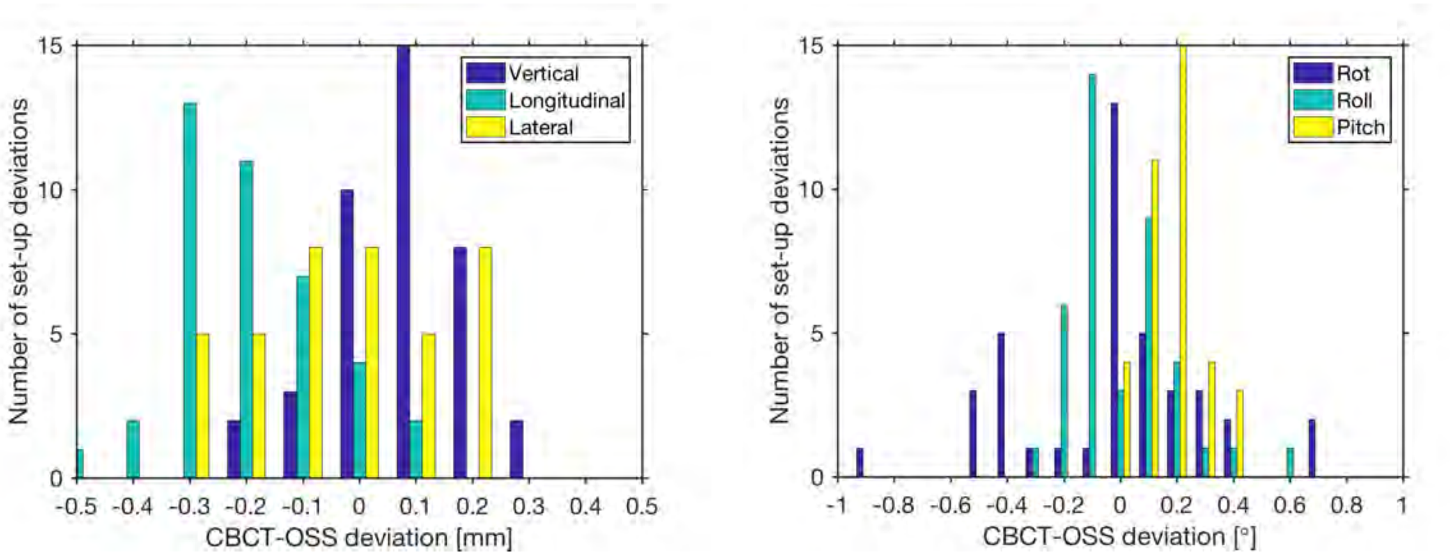
Figure 14: Agreement between $\mu_{\text{(ref-CBCT)}}$ and $\mu_{\text{(ref-OSS)}}$, in the vertical (a), longitudinal (b) and lateral (c) direction.



a b

Figure 15: Total translational (a) and rotational (b) agreement between $\mu_{(\text{ref-CBCT})}$ and $\mu_{(\text{ref-OSS})}$, for all four isocenters.

Patient positioning using the OSS system used in this thesis has recently been evaluated by Stieler et al. in a clinical study and in a phantom test [7]. The phantom test showed good agreement between the OSS system and on-board imaging with mean deviations within 0.52 mm and standard deviations within 0.41 mm. The clinical study showed a mean deviation between the CBCT and OSS system for head-and-neck patients within 3.7 mm and 0.9° and standard deviations within 3.4 mm and 1.8°. With a similar system, Align RT™ (Vision RT, London, United Kingdom), Gopan et al. found a error of 2.4-4.5 mm and 0.8-2.2° in a clinical head-and-neck study [15].

For SRT treatments, the demands on patient positioning are even higher than for head-and-neck treatments. It is therefore of utmost importance that the OSS system is accurate. The CBCT system within this study has been well documented and calibrated to the treatment isocenter. The agreement between the OSS system and the CBCT system was within 0.5 mm in all translational directions and within 0.9° in the rotational directions, thus indicating similar agreement as the phantom study performed by Stieler. et al. The systematic error in the longitudinal direction was reproduced in the comparison, which further indicate that there is a misalignment between the OSS system and CBCT system in the longitudinal direction.

The results show submillimeter agreement between the CBCT system and the OSS system for a phantom when the couch is in 0°. Thus, the OSS system has the potential to position patients at 0° with the same accuracy as with CBCT, which today is used as the gold standard. Furthermore, the results are within the tolerance of 1 mm suggested by the AAPM (American Association of Physicists in Medicine) TG142, for coincidence of radiation and mechanical isocenter [23]. Although the results cannot be directly compared with the set-up data from SRT patients previously treated at the clinic with conventional closed masks, the clinic is now prepared to initiate a patient study to collect data from patient positioning using the OSS system and open masks and thus be able to directly compare set-up with conventional masks versus open masks. This phantom experiment was a crucial step in order to initiate the patient study, since the SRT algorithm used for the OSS system in this thesis had not been previously clinically evaluated.

4.3 Positioning for non-coplanar treatments

4.3.1 OSS-indicated offsets

For the OSS-indicated shifts for non-coplanar treatments, the median displacement in the vertical direction was -0.2 mm for all couch angles (Figure 16). The median displacement for 90° was 0.1 mm in the longitudinal direction and -0.9 mm in the lateral direction. The median displacement of 270° was 0.7 mm in the longitudinal direction and 0.1 mm in the lateral direction. The median rotational displacement were 0° for couch angle 90° and -0.5° for couch angle 270°.

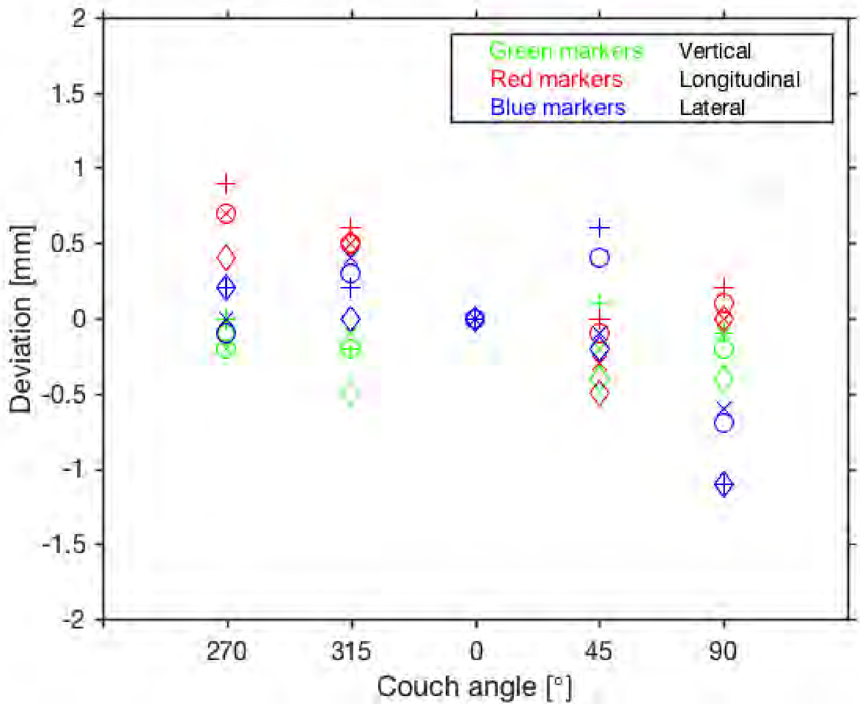


Figure 16: OSS-indicated shifts at couch angles 0°, 45°, 90°, 270° and 315°. The different markers represent each of the four PTVs.

The results (Figure 16) show that for a phantom, the OSS system indicate that when rotating the couch to different couch angles, the position of the phantom relative to the treatment isocenter is shifted. This is most prominent in the longitudinal and lateral directions. As previously discussed, the source of the OSS-indicated deviation is difficult to identify, but it could be due to a misalignment between OSS isocenter and treatment isocenter. If there is a small misalignment between those, the offset will increase when rotating the couch, since the two systems will not rotate around the same axis (Figure 17). The cause of the OSS-indicated shift may also be due to couch offsets, which means that the couch has a mechanical tolerance. In 0° the treatment isocenter and couch isocenter are aligned, but when rotating the couch there is an offset between the treatment isocenter and couch isocenter (Figure 18). It may also simply be due to uncertainties in the OSS system calculation of the shift.

Non-coplanar SRT treatments requires perfect alignment between the treatment beam axis, couch axis, and OSS-isocenter such that the axises remains constant while any of these components change position.

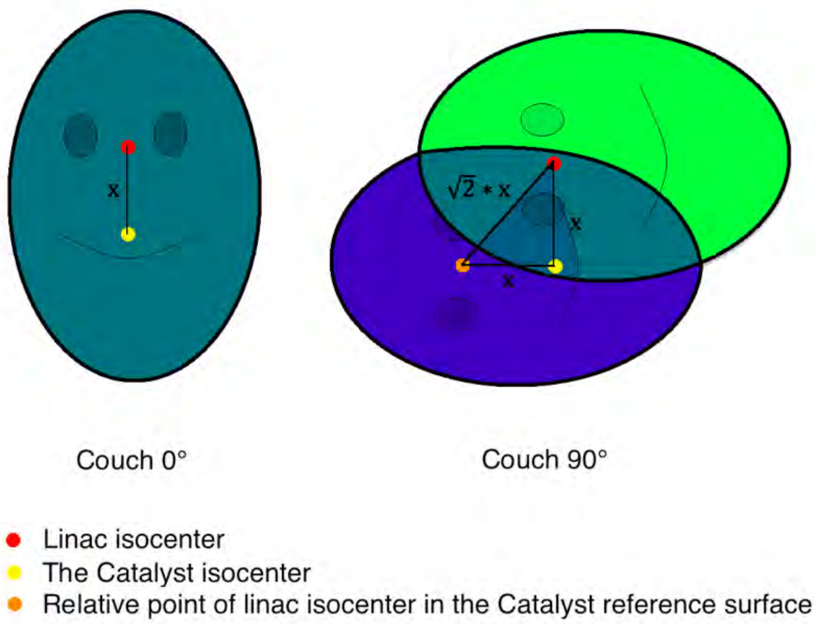


Figure 17: Illustration of the effect of a misalignment between the treatment isocenter and the OSS systems isocenter when rotating the couch [22].

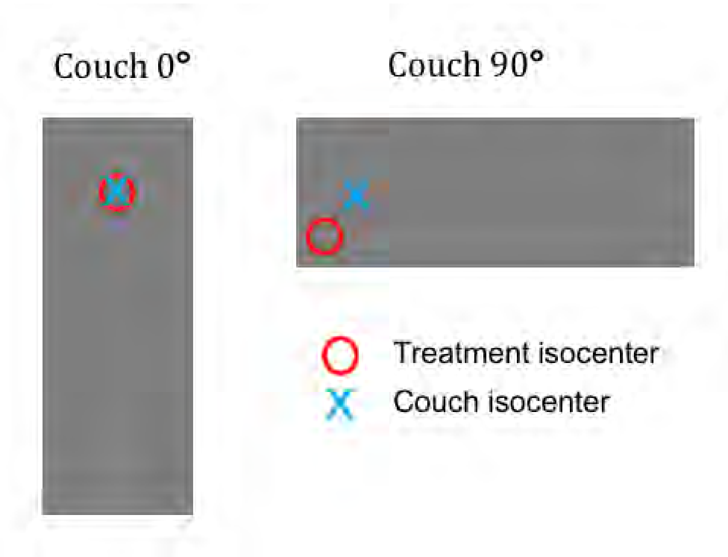


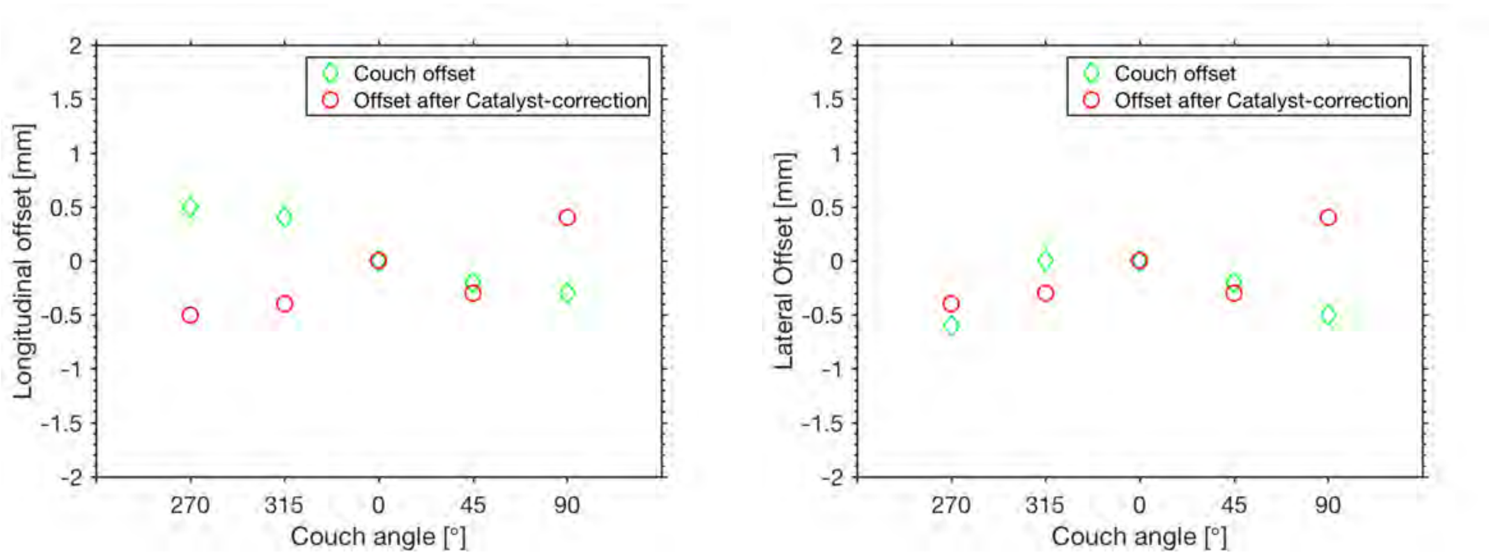
Figure 18: Illustration of the effect of a couch rotation offset.

4.3.2 Validation of positioning

The couch within this study has an offset when rotating the couch, that is larger for larger couch rotations (green markers in Figure 19). The largest offset of 0.6 mm was found at couch angle 270° in the lateral direction. The OSS system has an uncertainty in the calculation of the isocenter position that is within 0.5 mm (red markers in Figure 19).

The results show that the OSS system is able to validate patient position with an accuracy of 0.5 mm for couch angles $\neq 0°$ in the longitudinal and lateral direction. The uncertainty in the isocenter calculation was also noticed during the experiment, as the isocenter shifts suggested by the OSS system was fluctuating.

Within this study, the couch offsets were small (about the same order as the uncertainty of the OSS system calculation of the isocenter shift), and thus the results do not prove that a correction of position according to the OSS system would decrease the deviation from treatment isocenter. However, by tracking the surface, no additional uncertainties are introduced and thus there do not seem to be a problem when using the OSS system to monitor the phantom in these couch angles. The results give a good indication that the OSS system can be used as a tool to monitor patient position at couch angles $\neq 0°$, with the same accuracy as for couch angle 0°. At the clinic, the QC process allows for a couch offset within a radius of 2 mm from the treatment isocenter. The results suggest that the OSS system is able to identify and correct for couch offsets to achieve a positioning with an accuracy of 0.5 mm.



a b

Figure 19: The isocenter offset (greeen markers) from couch angle 0° to couch angles 45°, 90°, 270° and 315° respectively in the longitudinal (a) and lateral (b) direction together with the offset after couch correction according to the OSS-indicated values (red markers). All values are presented according to the couch coordinate system, as position of the steel ball relative to the treatment isocenter.

Since CBCT can only be acquired at couch angle 0°, the experiment carried out in section 4.3.2 was the method chosen to validate patient positioning at couch angles $\neq 0°$. With the QA tools typically available today, it is hard to determine the couch offset with submillimeter precision. As non-coplanar treatments become more common, a more efficient method for accurate measurement of couch offset is preferable. The limitation of this experiment is the validation of patient position in the vertical direction. However, results of the OSS-indicated deviations in section 4.3.1 in the vertical direction are close to zero for all couch angles. Thus it is assumed that the OSS system is able to calculate the isocenter shift in this direction with the same accuracy as for the longitudinal and lateral direction.

Note, to be able to rely on the OSS system and use it as a tool to correct the patient position in all couch angles, the QA procedures are critical. The TG142 report suggest daily QA of imaging and treatment coordinate coincidence and annual QA of couch rotation isocenter [23]. Furthermore, it is important to properly execute the Routine QA prior to SRT treatments to align the OSS systems isocenter and the treatment isocenter.

4.3.3 OSS-indicated offsets for intentional misalignment

The magnitude of the total isocenter shifts indicated by the OSS system at couch angles $\neq 0°$ for the intentional misalignment between the treatment isocenter and the OSS system's isocenter were larger for the larger misalignment (Figure 20). For a miscalibration of +1 mm in the longitudinal direction the average induced isocenter shift when rotating the couch in 90° and 270° was 1.4 ± 0.3 mm and 1.3 ± 0.4 mm, respectively. Based on geometry, the isocenter shift suggested by the OSS system at couch angles ±90° should be $\sqrt{2}$ * the magnitude of the misalignment (see the illustration in Figure 17). For 1 mm misalignment, this would be 1.4 mm. For a miscalibration of +3 mm in the longitudinal direction the average induced isocenter shift when rotating the couch in 90° and 270° was 3.7 ± 1.0 mm and 4.3 ± 0.5 mm, respectively. Based on geometry, the expected OSS-indicated isocenter shift would be 4.2 mm. The largest shifts were seen in the longitudinal and lateral directions. The vertical direction was not effected since the couch is rotating around the vertical axis.

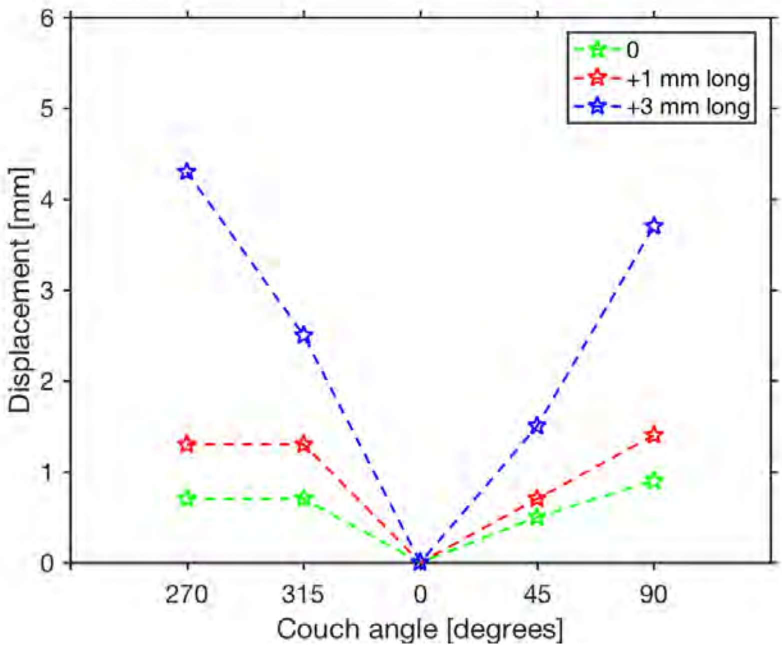


Figure 20: The magnitude of the total isocenter shifts indicated by the OSS system at couch angles ≠ 0°, with and without an intentional misalignment between the treatment isocenter and the OSS systems isocenter.

These results demonstrate the importance of the Routine QA to align the OSS system to the treatment isocenter before any SRT treatment. A misalignment between the two system may cause large isocenter shifts and effect the outcome of the treatment. Note, the QC procedure for the CBCT system only allow drift between CBCT isocenter and treatment isocenter of 1 mm, indicating that it is not likely with miscalibrations as large as 3 mm.

4.4 Dosimetric effect of positioning uncertainties

In the original plans the PTV V(95%) coverage is always close to 100%, but when applying the isocenter shifts in the uncertainty plans the PTV coverage decrease drastically (Table 7).

Table 7: V(95%) for fifteen PTVs from clinical treatment plans and their corresponding uncertainty plans.

	Dose [%] **Original plan**	Without OSS Dose [%] (min-max) **3.4 mm shift**	With OSS Dose [%] (min-max) **1.9 mm shift**
PTV 1	98.9	82.4 - 87.1	91.3 - 93.7
PTV 2	99.1	85.6 - 91.6	92.5 - 97.2
PTV 3	99.4	86.8 - 92.1	93.8 - 97.0
PTV 4	99.6	81.1 - 88.6	91.7 - 97.2
PTV 5	99.8	87.8 - 94.5	95.4 - 98.8
PTV 6	99.7	91.1 - 96.0	96.0 - 98.2
PTV 7	98.3	76.7 - 86.5	87.2 - 95.2
PTV 8	99.5	80.2 - 85.7	89.9 - 95.0
PTV 9	99.9	82.8 - 85.8	93.0 - 94.3
PTV 10	100	86.6 - 95.2	95.1 - 99.4
PTV 11	100	96.4 - 97.9	99.1 - 100
PTV 12	100	88.2 - 94.9	96.1 - 99.1
PTV 13	100	87.6 - 89.8	94.1 - 95.9
PTV 14	99.4	78.7 - 86.3	88.4 - 95.2
PTV 15	99.2	88.6 - 95.4	95.9 - 98.9

The results show that for non-coplanar treatments, the worst-case scenario at the clinic today entails a risk of V(95%) decreasing to 76.7% (PTV 7). This scenario includes 1 mm drift of CBCT isocenter from treatment isocenter at couch angle 0°, as well as a couch offset of 2 mm when rotating the couch. This may lead to insufficient radiation dose to the target which reduces the chance of curing the patient. Another effect is that OAR may be exposed to higher doses than tolerated, thus be damaged and cause treatment-related complications for the patient.

The results demonstrate the importance of accurate patient positioning throughout the whole treatment. With the OSS system as a complement for patient positioning at couch angles $\neq 0°$, it is possible to avoid large isocenter shifts caused by couch offset. In that case, the worst-case V(95%) would be 87.2%. Even though this is not an optimal number, it is a great improvement from 76.7%.

5 Conclusions

In this master thesis the potential of using an optical surface scanning (OSS) system in combination with open-face masks to improve patient positioning was evaluated. It has been concluded that the set-up accuracy for the OSS system within this thesis and its new SRT algorithm is comparable to that of CBCT-verification, which today is the gold standard used at the clinic. Furthermore, the OSS system can validate patient position for all couch angles with an accuracy of 0.5 mm and be used as a tool to detect and correct for unwanted couch rotation offsets. As high accuracy and non-coplanar SRT treatments become more common, it is of increased importance to validate patient position at couch angles $\neq 0°$. The brain include many sensitive OAR, why it would also be preferable to monitor patients during the whole treatment. The evaluation of the dosimetric effect of patient positioning uncertainties in non-coplanar treatments show that, without the OSS system as a complement for patient positioning, the uncertainties may cause the PTV coverage to decrease drastically.

Non-coplanar SRT treatments require perfect alignment between treatment beam axis, couch axis, and OSS system isocenter. To achieve this, QA procedures verifying a small couch rotation offsets and alignment between the isocenter of the OSS system and the treatment isocenter, are critical for these types of treatments.

In summery, the OSS system within this thesis show good potential to improve patient positioning for SRT treatments. However, the system must be further tested on volunteers and patients before clinical implementation. This master thesis is the first step against commissioning of the OSS system and open-face masks for SRT treatments at the clinic.

6 Future prospects

The research presented in this thesis is the preparatory work for a clinical implementation of a new SRT workflow using the optical surface system and open-face masks to position and monitor patients with brain metastases. The OSS system has already been implemented in the clinic for other treatment areas, such as breast treatments, but before it can be implemented for SRT treatments and for treatments with couch rotations, it has to be concluded that the system provides sufficient accuracy for this purpose. In this thesis it has been concluded that the system provides sufficient precision for a phantom, and the clinic is now prepared to initiate a patient study to collect data from patient positioning using the OSS system and open masks and thus be able to directly compare set-up with conventional masks versus open masks. This phantom experiment was a crucial step in order to initiate the patient study, since the SRT algorithm used for the OSS system in this thesis had not been previously clinically evaluated.

As non-coplanar treatments become more widely used, there is a need for an accurate and efficient method to measure and adjust the alignment between the treatment couch rotation isocenter and the treatment isocenter. The standard method to assess the rotational alignment of the treatment couches used at the clinic today is by visual inspection of crosshair walkout (i.e. the crosshair position at a given couch angle, relative to the position at couch angle 0°). on a graph paper. The walkout is only determined in two dimensions and it is not possible to assess the walkout with submillimeter precision. Furthermore, the crosshair itself may be misaligned. It would be preferable to find a method that is more accurate and efficient for this purpose.

The couch offsets evaluated for the couch within this thesis were clinically relevant, since they are within the tolerance for couch offsets. However, it would be interesting to intentionally introduce a larger couch offset to investigate the performance of the OSS system in detecting larger shifts. If it is known that 1) the OSS system isocenter and the treatment isocenter are perfectly aligned, 2) a reference surface is captured by the OSS system before rotating the couch and 3) it is assumed that the OSS calculation of the isocenter shift, any displacement when rotating the couch would in theory be due to couch offsets. If this is the case, staff can correct the patient position according to the OSS system to compensate for the incorrect couch position.

Furthermore, in this thesis, the dosimetric effect of a isocenter shift was evaluated in terms of PTV coverage. It would also be interesting to evaluate how the OAR are effected of the isocenter shifts.

This type of high precision and high dose treatment is an interesting area of research. It would be a huge advantage if the patient motion could be controlled by real time monitoring during the whole treatment. This is particularly important when we irradiate areas with many sensitive organs at risk surrounding the tumor volume, such as the brain.

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