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Evaluation of intrafractional motion for patients receiving whole brain radiotherapy in open-faced immobilisation masks

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Popularized summary in Swedish

Patientrörelser under behandling vid bestrålning av hjärnan

Antalet cancerpatienter i Sverige ökar och varje år diagnostiseras över 60 000 fall. Den vanligaste formen av hjärncancer är hjärnmetastaser, som uppstår då cancer som har börjat någon annanstans i kroppen sprider sig till hjärnan. Hjärntumörer kan ge många symptom, såsom huvudvärk, balansproblem, illamående osv. och kan behandlas med läkemedel, kirurgi eller strålning. För patienter med många hjärnmetastaser ges en palliativ (symptomlindrande) behandling där hela hjärnan bestrålas.

För att behandlingen ska ges korrekt är det viktigt att patienten ligger stilla och att de ligger likadant vid varje behandlingstillfälle, varför patienten fixeras under behandling. För patienter som får strålbehandling mot hjärnan används konventionellt en heltäckande plastmask som gjuts efter patientens huvud och fästs i britsen. De övervakas också under behandling med ett optiskt ytskanningssystem (OSS-system), som skannar av patientens yta och beräknar dennes position i rummet kontinuerligt. Eftersom fixationsmasken täcker patientens huvud kommer OSS-systemet endast att upptäcka hur masken rör sig, vilket inte nödvändigtvis är detsamma som patienten. För en noggrann rörelseövervakning vill vi kunna övervaka patienten direkt. Dessutom är fixationsmasken ofta obehaglig för patienter och en källa till behandlingsrelaterad ångest för många.
På grund av detta finns en önskan att börja använda så kallade öppna masker istället som har en öppning över patientens ansikte. Det skulle möjliggöra OSS-systemet att övervaka patientens yta över ansiktet och därmed upptäcka patientens rörelser, inte bara maskens. En öppen mask är även mindre obehaglig för patienten. Dessa masker skulle dock kunna tillåta att patienten rör sig mer inuti masken jämfört med en heltäckande mask.

Detta examensarbete undersöker mängden rörelse under behandling för patienter som får strålbehandling mot hela hjärnan i en öppen fixationsmask. Under behandlingen övervakas patienterna med OSS-systemet som då också samlar in data om patienternas rörelser. 5 patienter som fick behandling under 5 tillfällen vardera inkluderades i studien och därmed kunde rörelsedata från 25 behandlingstillfällen analyseras. Den eventuella påverkan på kvaliteten på behandlingen från patienternas rörelser undersöktes även.

Arbetets resultat visar på att patienternas rörelser under behandling i den öppna masken ligger inom gränserna för vad som kliniskt kan accepteras och att påverkan på behandlingskvaliteten var försumbar. Detta innebär att dessa masker kan börja användas för alla patienter som får behandling mot hela hjärnan i kliniken, i kombination med ett OSS-system som övervakar patienten i real-tid.

Abstract

Purpose/Background
Patients receiving whole brain radiotherapy (WBRT) today are treated with an immobilisation mask which fully covers their face and therefore might be experienced as uncomfortable and claustrophobic. In recent years, optical surface scanning (OSS) systems have been implemented for patient positioning and real-time motion monitoring [1]. OSS systems cannot track the patients surface through the closed masks and are therefore only monitoring the motion of the mask. Using open-faced immobilisation masks would allow the OSS to monitor the patient directly, but may allow for more movement. The purpose of this thesis was to evaluate the intrafractional motion of WBRT patients receiving treatment in open-faced immobilisation masks.

Material and Methods
The accuracy of the x-ray and surface imaging system (EXTD) was investigated using two different rigid head phantoms with internal bony anatomy for matching purposes. The surface imaging is dependant on the phantoms optical characteristics [1] and therefore two different skin colours were used. The phantoms were placed on the treatment couch in nine different rotational angles and the position was verified with CBCT (Cone Beam Computed Tomography). The surface imaging and x-ray systems were compared to the CBCT using a Wilcoxon signed-rank test ($\alpha = 0.05$). The patients included in this study all received WBRT in open-faced immobilisation masks and were monitored using the combined surface and x-ray imaging capabilities of the ExacTrac Dynamic system. In total, 25 treatment fractions from 5 patients were analysed.

Results
Overall, both x-ray and surface imaging agreed with the CBCT within 0.4 degrees for all investigated angles. The largest deviation was 0.4 degrees and 0.3 degrees in pitch and yaw rotations for the x-ray imaging and surface imaging, respectively. No statistically significant difference was found between the x-ray and CBCT in the roll direction ($p>0.05$, both phantoms). For the other rotational directions there was a statistically significant difference ($p<0.05$) between the x-ray and the CBCT for both phantoms and all directions showed a statistically significant difference ($p<0.05$) between the surface and the CBCT for both phantoms.
For all five patients, the median (range) translational vector was 0.3 (0.0-1.3) mm, and 95% of the vector deviations were within 0.7 mm. For the individual translational directions, the absolute median (range) was found to be 0.1 (0.0-1.0) mm in lateral (lat), 0.2 (0.0-1.1) mm in longitudinal (long), and 0.1 (0.0-0.7) mm in vertical (vert), respectively, and for the rotational directions 0.1 (0.0-0.8) degrees in pitch, 0.1 (0.0-0.7) degrees in roll, and 0.1 (0.0-0.7) degrees in yaw, respectively. 95% of the deviations were within 0.4 mm in lat, 0.6 mm in long, 0.3 mm in vert, 0.5 degrees in pitch, 0.3 degrees in roll, and 0.5 degrees in yaw.

Conclusion
For the two head phantoms, excellent agreement was observed for both x-ray and surface imaging compared to CBCT (within 0.4 degrees), which fulfills the QA guidelines published by ESTRO-ACROP and AAPM TG-302 [1, 2]. The EXTD system's accuracy showed no dependance on the colouring of the phantoms. This study shows that the surface guidance real time tracking of the patient's rigid face structures can detect submillimeter patient motion and in combination with its beam hold capabilities, deliver a high-accuracy treatment in the open face masks. The median intrafraction motion observed was 0.3 mm for all patients, and hence, open-faced masks can further be investigated for other patient groups.

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My special thanks to my supervisors:

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Abbreviations

AAPM American Association of Physicist in Medicine

CBCT Cone Beam Computed Tomography

CT Computed Tomography

DoF Degrees of Freedom

DRR Digitally Reconstructed Radiographs

D98% Dose received by 98% of the target volume

EXTD ExacTrac Dynamic®

Lat Lateral

Linac Linear Accelerator

Long Longitudinal

MV Megavoltage

OSS Optical Surface Scanning

PTV Planning Target Volume

QA Quality Assurance

ROI Region-of-interest

RT Radiotherapy

SGRT Surface Guided Radiotherapy

SRS Stereotactic Radiosurgery

SL Structured Light

TPS Treatment Planning System

Vert Vertical

VMAT Volumetric Modulated Arc Therapy

WBRT Whole Brain Radiotherapy

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1 Introduction

The incidence of cancer in Sweden is gradually increasing. In 2021 roughly 68 000 patients were diagnosed with cancer, a slight increase compared to 2020 [3]. However, with the continuous development of new diagnostics and treatments, cancer mortality is gradually decreasing.

The most common form of intracranial malignancies are brain metastases and they occur in 10-30% of all cancer patients [4]. There a few different types of cancer that commonly metastasise in the brain, such as breast, lung, and kidney cancers [5]. The symptoms most commonly seen in patients with brain metastases arise from heightened intracranial pressure due to the tumour growth, and are, for example, headache, nausea, visual field defects, and balance problems [5–8]. There are two different techniques for treating brain metastases with radiotherapy (RT), stereotactic radiosurgery (SRS) and whole-brain radiotherapy (WBRT). SRS is used for patients with fewer metastases, since it gives lower dose to healthy tissues, while WBRT delivers the same dose to the whole brain and is therefore used to treat patients with multiple brain metastases [4].

To help WBRT patients keep still on the treatment couch, they are immobilised with a thermoplastic mask in combination with a neck support [9]. The current standard practise is to use a mask which fully covers the face, which studies show can be the cause of treatment-related anxiety for many patients [10–12]. There have been instances of patients ending their treatment early or choosing to forgo treatment altogether due to finding the mask intolerable. Additionally, optical surface scanning (OSS) systems, which have begun to be used in many clinics [13] to monitor patient motion during treatment, cannot track the patient through the mask. Therefore, when used in combination with a mask that covers the patients face, the OSS system monitors the motion of the mask, not the patient, and hence, the motion detected may not be completely accurate. In the last few years, open masks, i.e. masks that are open over the patients face, have started being manufactured and are used in some clinics [14]. The benefits of an open mask is that the OSS system will track the patient's surface instead of the mask, and they might be more tolerable to patients. The drawback of open masks is that they might allow for more head motion within the mask, which could impact the overall quality of the treatment. Therefore, it would be preferable to implement open masks in combination with real-time tracking using an OSS system with beam-hold capabilities to monitor the patient's motion during treatment and interrupt the beam should the patient move out of certain pre-set tolerances [1]. There have been a few studies investigating open-faced masks for their immobilisation abilities and patient comfort, which have found improved tolerance for patients with claustrophobia as well as an accuracy within 3 mm [14–17].

Firstly, we want to investigate the accuracy of the ExacTrac Dynamic systems surface and x-ray imaging by comparing them to the CBCT (Cone Beam Computed Tomography) system of the TrueBeam linac. Surface imaging is dependant on the phantoms optical characteristics [1] and therefore two different head phantoms were used in different colours. Then, using the ExacTrac Dynamic system, we want to track the intrafractional motion of patients receiving WBRT in open-faced masks, to assess if this could be an option offered to all WBRT patients in the clinic. Surface imaging can track the patients motion in real-time, while x-ray images are taken at discrete intervals during treatment.

The purpose of this thesis was to evaluate the intrafractional motion of WBRT patients receiving treatment in open-faced immobilisation masks using real-time surface imaging and x-rays. The study was conducted at the radiotherapy clinic at Skåne University Hospital in Lund.

2 Background

2.1 Whole brain radiotherapy

Whole brain radiotherapy (WBRT) is a method for treating brain tumours with radiation. It is mostly used for palliative treatment of brain metastases [4] and sometimes as a prophylactic treatment for patients with small-cell lung cancer. The goal of WBRT for palliative treatment is to control the local disease and prevent progression, thereby alleviating the symptoms of heightened intracranial pressure that so many patients experience [7, 8]. This could allow for a lower dose of palliative care medicines, such as corticosteroids [7]. By controlling/alleviating symptoms the patients quality of life can be maintained for a longer time period [7, 8].

There are different possible fractionation schemes in use today, such as 30 Gy/10 fractions, 25Gy/10 fractions and 20 Gy/5 fractions, that are usually delivered with a 10 MV photon beam [8]. In our clinic patients with multiple brain metastases who receive palliative care are typically treated with WBRT, using a 20 Gy/5 fractions, 1 fraction/day fractionation scheme, and a 10 MV photon beam. The treatment is delivered with two opposing static fields angled from the side of the head. Alternatively, two rotational VMAT fields are sometimes used when the patient has received previous radiotherapy in the same or adjacent area in order to spare organs at risk. A fractionation scheme of 30 Gy/15 fractions is also used, sometimes, for patients in good general condition. Patients receiving prophylactic treatment with WBRT are treated with a 25Gy/10 fractions, 1 fraction/day fractionation scheme, and a 10 MV photon beam [9].

2.2 Optical Surface Scanning

Optical surface scanning (OSS) systems have become widely used in radiotherapy for patient set-up and real-time intrafraction motion monitoring. OSS systems reconstruct the 3D surface of the patient in real-time with optical imaging. Since they are non-ionising they can be used daily without any added risk of radiation-induced malignancies [1, 2]. The OSS system in use at the clinic is the ExacTrac Dynamic® by BrainLAB AG (Munich, Germany).

The ExacTrac Dynamic® (EXTD) system consists of both an x-ray system with two in-floor x-ray tubes and two ceiling mounted flat panel detectors, and a single ceiling mounted surface scanning camera mounted centrally above the treatment couch (see figure 1). The ceiling mounted camera includes one light projector, two cameras and an integrated thermal camera [19]. With this the system can reconstruct a 3D surface of the patient and match it, using a rigid algorithm, to a reference surface to find the couch shifts needed for a perfect match. The reference surface can be constructed from the external contour of the CT (Computed Tomography) image or be captured in the room using the system cameras [1, 2, 19]. To acquire the surface data the system projects a patterned light onto the patient, also known as structured light (SL). Since the surface of the patient is not flat the pattern will be distorted when reflected back to the cameras, which will then allow the system to calculate the surface structure [19].

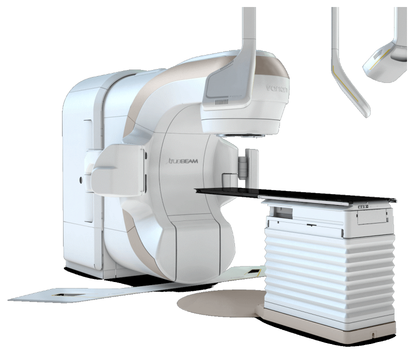


Figure 1: The ExacTrac Dynamic® integrated with a Varian TrueBeam linac [18].

The integrated thermal camera provides an extra dimension of information for the system to use when matching the live surface to the reference. The EXTD OSS system uses the Perspective-n-point algorithm to correlate the 3D surface points with the 2D thermal data to create a hybrid 3D/thermal matrix. Figure 2 is a visual display of this process and shows how adding the thermal information creates a virtual topography that aids in surface matching. By incorporating this "extra" dimension into the matching of the surfaces, a higher accuracy and faster matching can be achieved [19]. One of the challenges with surface guided radiotherapy (SGRT) is that the surface can be difficult to render for very dark skin tones due to the lower amount of reflected light [1, 19]. This problem is mitigated by the thermal imaging since there is additional information to use to render the surface [1].

The floor-mounted x-ray tubes are independent from the linac (linear accelerator) and can therefore be used to quickly acquire images with bony structure for final positioning or verification during treatment [19].

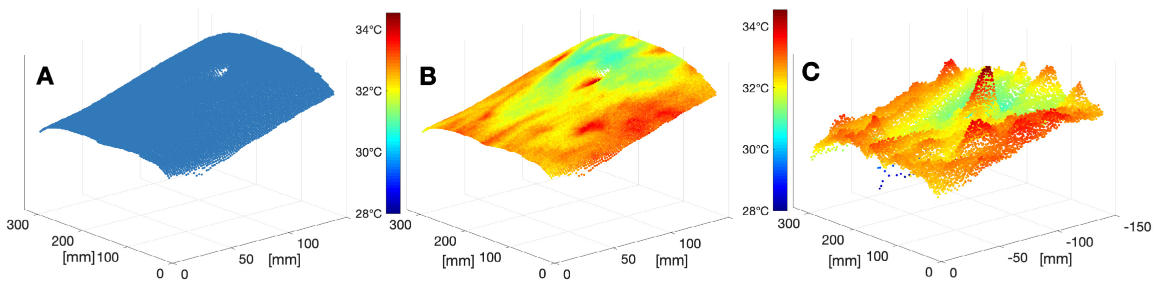


Figure 2: These graphs illustrate how the EXTD OSS system incorporates thermal information. **A** shows only the surface information, **B** shows the thermal information as a colour map overlay on the surface, and **C** shows the combined surface and thermal information [19].

2.2.1 Patient positioning

Patient positioning is performed in EXTD using the prepositioning mode. In the clinic the external contour from the CT scan is used as the reference surface in this mode, as it is the planned position during CT that is to be replicated during treatment [19]. The live surface is registered to the reference surface in 6 degrees of freedom (DoF), enabling the calculation of three translational shifts (lat, long, vert) and three rotational shifts (pitch, roll, yaw) [1, 2], as well as a translational vector ($=\sqrt{lat^2+long^2+vert^2}$). These shifts can then be sent to the treatment system, allowing the couch to be moved to the correct position [2].

The final positioning is performed using stereoscopic x-ray images from the integrated x-ray system [19], matching the internal anatomy to the digitally reconstructed radiographs (DRR:s) created from the CT image.

2.2.2 Real time monitoring

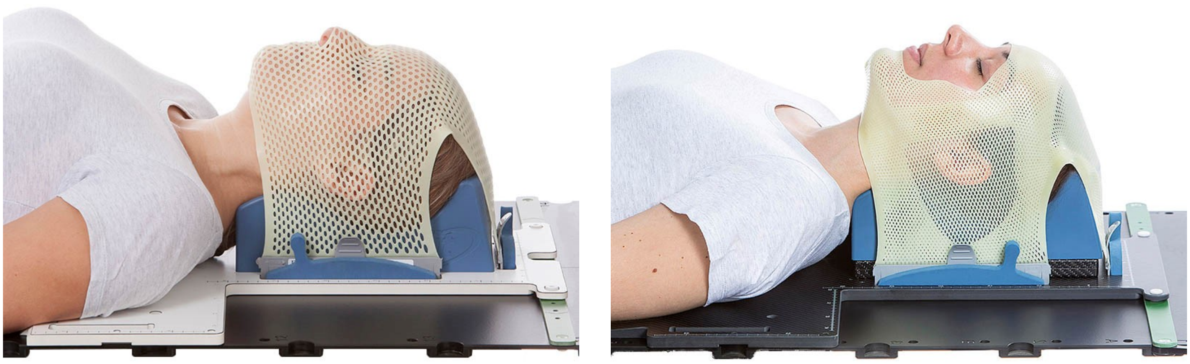
The monitoring mode is used for real time monitoring of patient motion during treatment. For this mode the last surface registered in the pre-positioning mode, after the final positioning using the x-ray images, is used as the reference surface [19]. The OSS system is continually comparing the live surface to the reference surface and any inconsistencies between the two that are detected are displayed to the personnel, both as individual deviations in 6 DoF and as a

graph of the translation vector [2]. During the treatment the ExacTrac x-ray system can be used to acquire new images at any point to monitor the position using internal anatomy. These are automatically matched to the DRR:s and the deviations in 6 DoF are displayed. After every x-ray acquisition the OSS system records a new reference surface including updated thermal information [19]. This adjustment is done so that the OSS system and the x-ray system agree on the correct patient position. The system can be set to take a certain number of x-rays per beam, triggered on either gantry angle (for rotational beams) or on MU delivered (for static beams), or taken manually during treatment.
The system can be set to automatically interrupt the treatment beam if patient motion outside the set thresholds is detected by either the OSS system or the x-ray system.

2.3 Immobilisation

Immobilisation of patients is critical for safe and reproducible treatments [20]. Patients with head and neck cancers are typically immobilised with a thermoplastic full-head mask (figure 3a), which is fitted to each patient shortly before the planning CT and then used to immobilise the patient in a reproducible position throughout the treatment. These masks have been well characterised in terms of head motion within the mask and setup uncertainties, allowing the calculation of treatment margins. However, full-face masks force patients to keep eyes and mouth closed during treatment, which can be uncomfortable and anxiety-inducing for many patients [10–12, 15]. These masks also obstruct the patients face from the OSS system, so the system is monitoring the mask motion rather than patient motion.

An open-faced thermoplastic immobilisation mask, seen in figure 3b, allows the OSS system to track the patients face directly and to monitor the patient's motion. They have also been found to be tolerable to patients with claustrophobia [15] and will likely be more comfortable for all patients. Several studies have also found that patients' motion within open-faced immobilisation masks is within the same range as for full-head masks [14–16].



(a) **(b)**

Figure 3: Thermoplastic immobilisation masks used for brain treatment. A closed full-head mask (a), and an open-faced mask (b) by Orfit Industries (Wijnegem, Belgium) [21].

3 Material and Methods

This masters work consists of two parts. The first is a phantom study which aimed to investigate the agreement between the three position verification systems on the linac, the OSS system and the x-ray system in the EXTD, and the CBCT. The study utilised two different anthropomorphic cranial phantoms, the STEEV phantom (CIRS Inc, Norfolk, VA, USA) and the cranial verification phantom from BrainLAB AG (Munich, Germany). These two phantoms were chosen since they are different colours (see figure 4) and as OSS systems tend to be less sensitive to darker skin colours, it might be interesting to investigate if there are any differences between them.
The second part of this masters work looks at the intrafractional motion of patients treated for WBRT with an open-faced immobilisation mask. Five patients treated with palliative WBRT in the clinic during the spring of 2023 were included in the study. Table 3 shows treatment specifics, such as fractionation and treatment technique, for the patients. For the patient who received 15 fractions, only the first 5 fractions were included in the study, to ensure that this patient did not dominate the result.

(a)

(b)

Figure 4: The phantoms used in the study; (a) the fair-coloured STEEV phantom [22], and (b) the dark-coloured cranial verification phantom from BrainLAB [23].

3.1 Phantom study

The first step of the phantom study was to CT-scan the phantoms and create a treatment plan. For the CT scan the phantoms were positioned as straight as possible on the treatment couch with aid of the in-room positioning lasers, and to keep them still a VacFix® vacuum bag (Par Scientific, Nyborg, Denmark) was used. A little bit of air was left in the vacuum bag to make it slightly flexible but still able to maintain its shape. The CT images were then reconstructed with the same reconstruction as is used for WBRT patients, and for the BrainLAB phantom metal reduction was added in the reconstruction to minimise the appearance of metal artefacts from the tungsten spheres it contains. A planning target volume (PTV) was created roughly in the isocenter of the CT image and a WBRT dose plan with two static opposing fields was then created, using Varian's Eclipse™ treatment planning system (TPS).
The phantoms were then positioned on the linac couch (TrueBeam® radiotherapy system, Varian Medical Systems) using the in-room lasers and different degrees of roll (-4°, -3°, ..., 3°, 4°) were introduced. These angles were chosen since, in the clinic, patients are repositioned for rotations over 3 degrees. For each angle, x-ray images were taken with the EXTD system and a CBCT with the on-board imaging system. The proposed couch shifts in 6 DoF were recorded during the procedure for all three imaging modalities/positioning systems (OSS, x-ray, CBCT). This procedure was then repeated for the other two rotational directions (pitch and yaw) as well.

Table 1: The resolution of the CT and CBCT images used.

	In-slice resolution	Slice thickness
CT	0.977 x 0.977 mm	2.0 mm
CBCT	0.511 x 0.511 mm	1.0 mm

3.1.1 Data evaluation

The CBCT was considered to be the gold standard for patient positioning in this study, and therefore the other two systems (EXTD Surface, and EXTD X-ray) were compared to the CBCT. A Wilcoxon signed-rank test ($\alpha = 0.05$) was used to test if the differences between the system were statistically significant. One plot per rotational direction and phantom was also made to visualise the data.

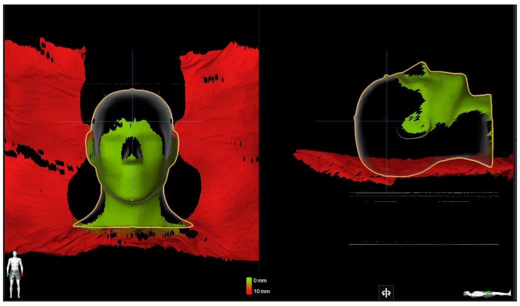


Figure 5: Surface-coverage (green colour) from the single-camera configuration of the EXTD system.

3.2 Patient preparation and treatment workflow

The first step for patients when they arrive in the clinic is the fixations and CT-scan. The patients included in this paper received an open-faced immobilisation mask from Orfit Industries (Wijnegem, Belgium) (see figure 3b). To mould the mask onto the patient it is first heated to 69°C and then allowed to cool down to roughly 55°C before being applied to the patient. The mask is then stretched into place and the three flaps fastened to the couch, while the edges of the open part of the mask are kept in place, to ensure it does not stretch out too much.
Once the mask has started to cool down and thereby stiffen up, the CT scan is performed. The mask needs about 10 minutes to cool down and harden before it can be removed from the patient.
After the planning CT has been performed, oncologists delineate the target and organs at risk. Dose-planners then create a treatment plan for the patient.
The patients received treatment on a TrueBeam® radiotherapy system with the PerfectPitch™ 6 DoF couch (Varian Medical Systems, Palo Alto, CA, USA) integrated with the ExacTrac Dynamic® system (BrainLAB AG, Munich, Germany). These systems in combination are able to interrupt the treatment beam and quickly reposition the patient in case of motion outside of tolerances. The patient is positioned on the treatment couch using the prepositioning mode in EXTD. The monitoring-ROI (Region Of Interest) is then chosen to include the parts of the face not covered by the mask, excluding the lips and lower jaw, since these do not affect the brains position (see figure 6a). Two sets of stereoscopic x-ray images are then taken and matched to the DRR:s on bony anatomy (see figure 6b). The first set is used to correct the patients position by applying the suggested couch shifts in all directions, including the rotational shifts. The second set is then taken to ensure the patient has not slid on the couch while the couch was moved. Treatment is then started and the patient is continuously monitored with the OSS and 1-3 stereoscopic x-ray images are taken per beam. Should the patient motion exceed a pre-set threshold a beam-hold is automatically induced and the patients position needs to be verified and corrected for using x-ray images before treatment can be resumed. The tolerances for this to occur can be found in table 2. A beam-hold occurred for one of the patients during the first fraction as they fell asleep on the treatment couch.

Table 2: Tolerances for the automatic beam-hold function for WBRT patients.

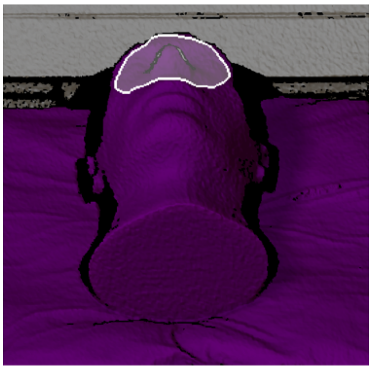
	Lat/Long/Vert [mm]	Transl. vector [mm]	Pitch/Roll/Yaw [deg]
Surface	2.0	2.5	1.5
X-ray	0.7	1.0	0.7

3.2.1 Data evaluation

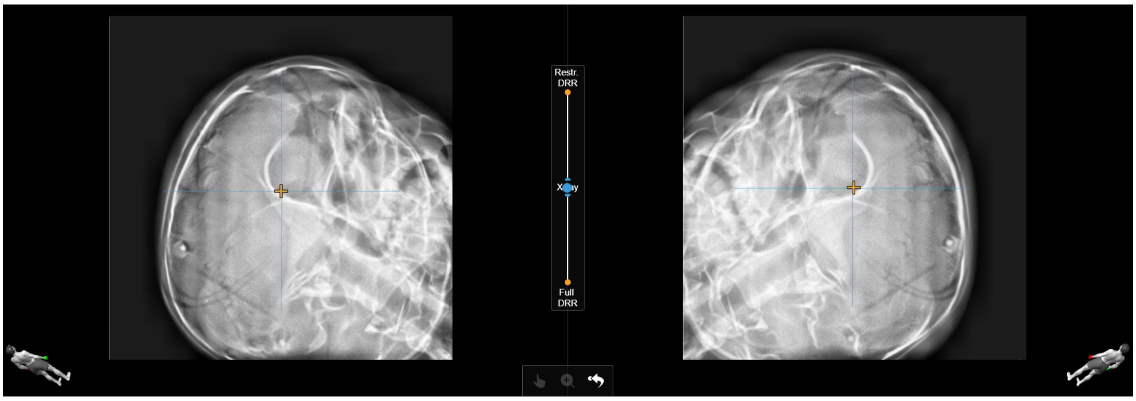
The data for all five patients was anonymised before being extracted from the system for analysis. In total, motion data from 25 fractions was analysed, and the median and the range was calculated for all 6 DoF and for the translation vector. To evaluate the dosimetric effects of this motion, two uncertainty plans were created in the ”External Beam Planning” mode in Varian's Eclipse™ TPS. The uncertainty plans were created with the largest positive deviations and the largest negative deviations to find the dosimetric effects of the largest shifts in both directions for each patient. This gives the dosimetric effect that would occur, should the patient be treated with this deviation throughout the entire treatment course.

Table 3: Patient and treatment characteristics.

Patient No.	**Sex**	**Fractionation**	**Treatment technique**	**No. of x-rays/fraction**
1	Male	20Gy/5f	VMAT	6
2	Female	20Gy/5f	Static	4
3	Female	20Gy/5f	VMAT	6
4	Female	30Gy/15f	Static	2
5	Male	20Gy/5f	Static	4



(a)



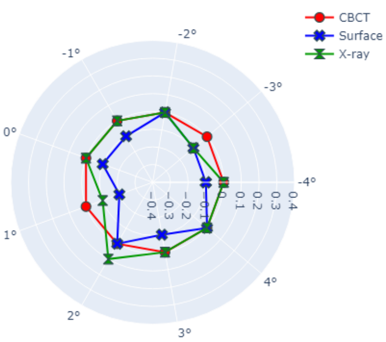
(b)

Figure 6: (a) The surface ROI used for the patients displayed on a cranial phantom. (b) Example of a set of two orthogonal x-rays that can be captured with the EXTD.

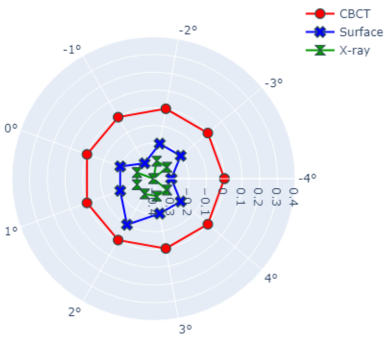
4 Results

4.1 Phantom study

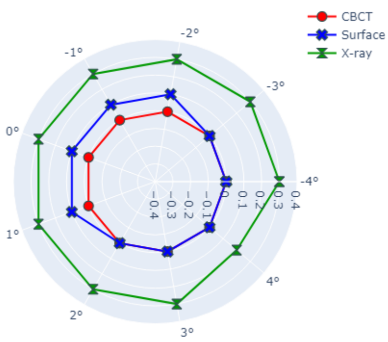
The spider plots in figure 7 visualise the differences between the measured rotations for the different systems. The values from the CBCT have been subtracted from the others to show the differences, which is why the CBCT line is constantly on zero.
The median of the differences between the x-ray system and the CBCT was 0.0 (0.0) deg in roll, 0.3 (0.3) deg in pitch, and 0.2 (0.3) deg in yaw, for the STEEV (BrainLAB) phantom. For the OSS system the median was 0.1 (0.1) deg in roll, 0.2 (0.0) deg in pitch, and 0.2 (0.2) deg in yaw, for the STEEV (BrainLAB) phantom.
The p-values from the Wilcoxon signed rank tests are presented in tables 4-5 below, and, as can be seen in the tables, most of the comparisons showed statistically significant differences (p<0.05) between the systems.



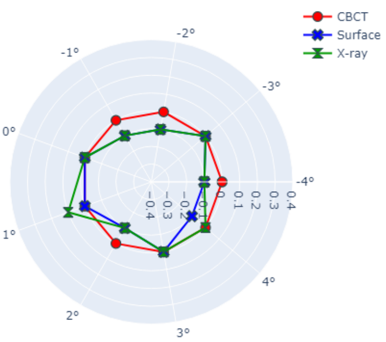
(a) BrainLAB phantom, Roll.



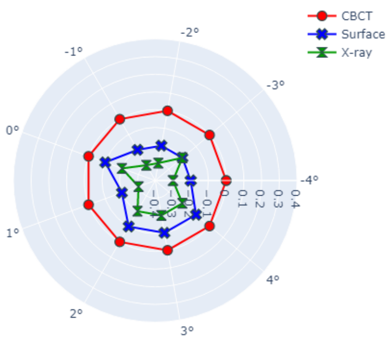
(b) BrainLAB phantom, Yaw.



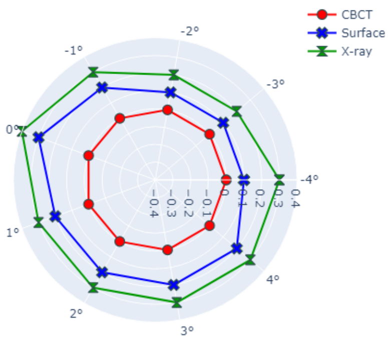
(c) BrainLAB phantom, Pitch.



(d) STEEV phantom, Roll.



(e) STEEV phantom, Yaw.



(f) STEEV phantom, Pitch.

Figure 7: The figures above display the difference in suggested couch shifts between the different imaging modalities and the CBCT, for the different rotational directions and phantoms.

Table 4: The *p*-values from the Wilcoxon signed rank tests on the BrainLAB phantom.

Rotational direction	Comparison	*p*-value*
Yaw	OSS vs. CBCT	0.006**
	X-ray vs. CBCT	0.005**
Roll	OSS vs. CBCT	0.020**
	X-ray vs. CBCT	0.564
Pitch	OSS vs. CBCT	0.046**
	X-ray vs. CBCT	0.004**

*The *p*-value was calculated using Wilcoxon signed-ranks test.
**Statistically significant result ($p<0.05$).

Table 5: The *p*-values from the Wilcoxon signed rank tests on the STEEV phantom.

Rotational direction	Comparison	*p*-value*
Yaw	OSS vs. CBCT	0.006**
	X-ray vs. CBCT	0.006**
Roll	OSS vs. CBCT	0.025**
	X-ray vs. CBCT	0.180
Pitch	OSS vs. CBCT	0.006**
	X-ray vs. CBCT	0.006**

*The *p*-value was calculated using Wilcoxon signed-ranks test.
**Statistically significant result ($p<0.05$).

4.2 Patient intrafractional motion

The median (range) of the translational vector for the intrafractional motion over all five patients was 0.3 mm (0.0-1.3 mm) and, as can be seen in the histogram of the vector deviations in figure 8, 95% of the deviations were within 0.7 mm. The median and range for the 6 individual directions is presented in table 6, and the histograms over these deviations are presented in figure 9 and show that 95% of the deviations are within 0.4 mm in lat, 0.6 mm in long, 0.3 mm in vert, 0.5 degrees in pitch, 0.3 degrees in roll, and 0.5 degrees in yaw, respectively. The largest deviation found in the D98% (the dose received by 98% of the target volume in percent of the prescribed dose), from the uncertainty plans, was a 0.7% difference. The dose distribution showed no visual difference in the dose received by the organs at risk (eye and lens).

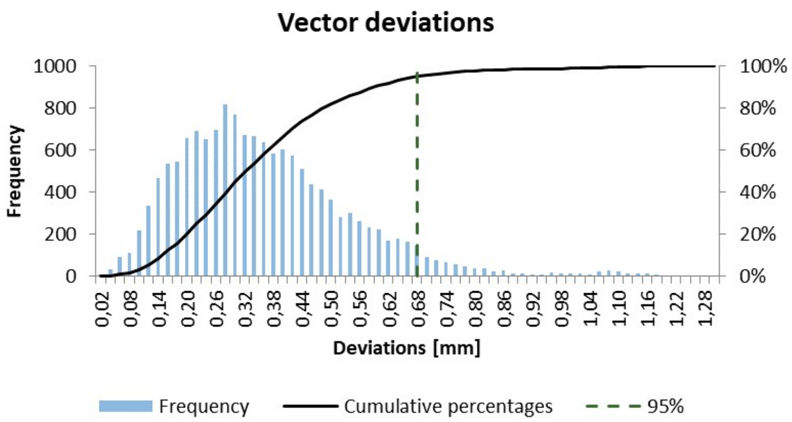


Figure 8: Histogram over the vector deviations from all five patients.

Table 6: Median and range of the absolute deviations in the 6 different directions.

	Lat [mm]	Long [mm]	Vert [mm]	Pitch [deg]	Roll [deg]	Yaw [deg]
Median	0.1	0.2	0.1	0.1	0.1	0.1
Range	0.0-1.0	0.0-1.1	0.0-0.7	0.0-0.8	0.0-0.7	0.0-0.7

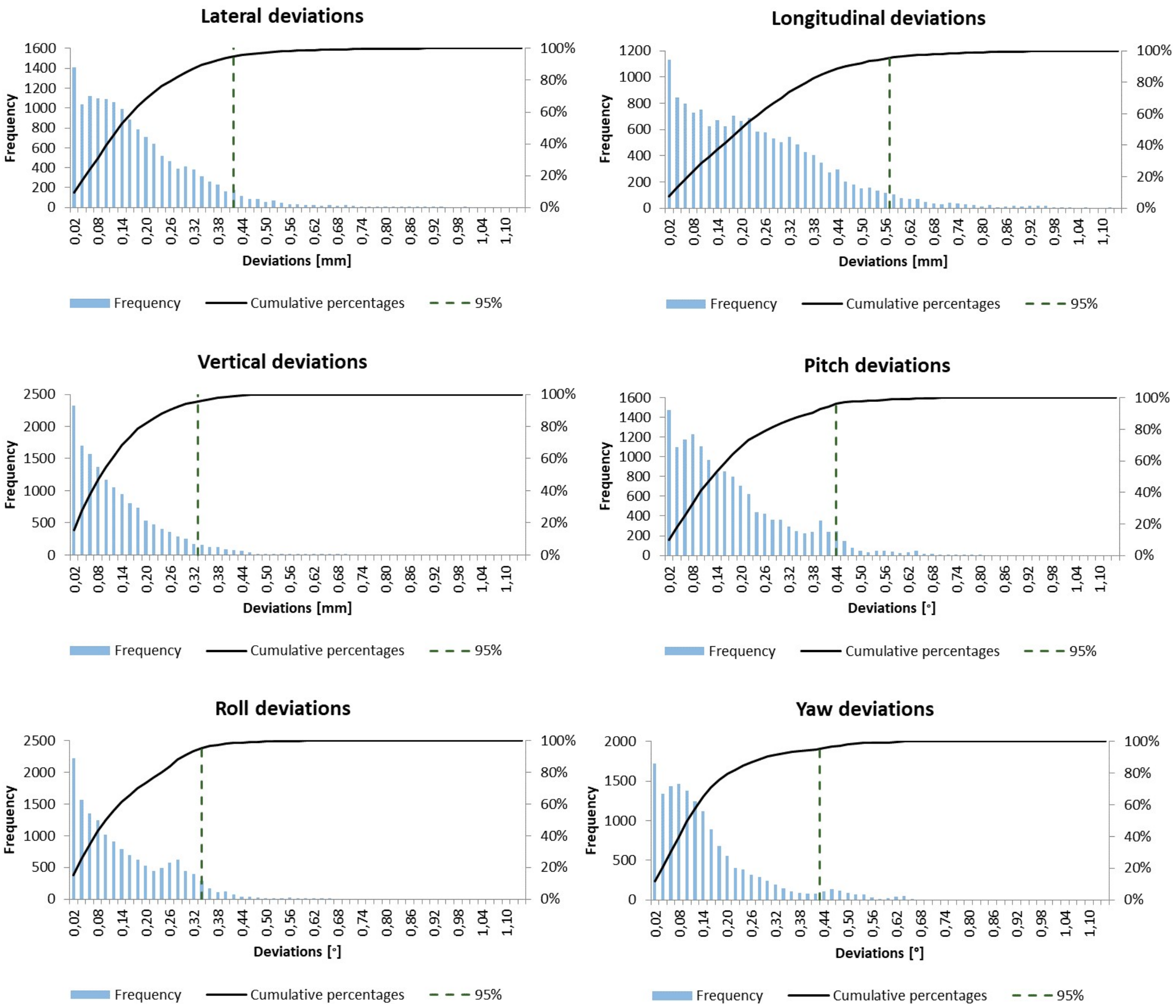


Figure 9: Histograms over the absolute deviations from all five patients in the 6 different directions.

5 Discussion

The overall result for the phantom study showed an agreement within 0.4 degrees between the surface and x-ray imaging systems compared to the CBCT, within the measurement range included (-4 to 4 degrees).
For the x-ray system, there was no significant difference ($p<0.05$) in the roll direction, however, differences were observed in the yaw and pitch directions, respectively, for both the fair and dark-coloured phantoms. The largest differences were observed for the x-ray system in the yaw and pitch directions with median deviations of 0.2, 0.3 and 0.3, 0.3 degrees for the fair-coloured STEEV and dark-coloured BrainLAB phantoms, respectively. A recent study conducted by Chow et al. also found no statistical difference in the roll direction for the x-ray system compared to the CBCT [24]. However, contrary to Chow et al, we found significant differences in the pitch and yaw directions for the x-ray system. Chow et al also found that the maximum difference was in the pitch direction for the x-ray system as we did, however, this study found a smaller maximum, 0.4 degrees compared to their 0.6 degrees.
For the surface imaging, smaller deviations in the yaw and pitch directions were observed compared to the x-ray system, with median deviations of 0.2, 0.2 deg and 0.2, 0.0 deg for the STEEV and BrainLAB phantoms, respectively. In the roll direction, surface imaging showed a larger deviation than the x-ray imaging, however, with only a small increase in the median deviation of 0.1 degrees. Our study shows, similarly to Chow et al, significant differences in the pitch and yaw directions, however, they did not find a significant difference in the roll direction, which we did.
Surface guided systems are dependant on the optical characteristics of the phantom being scanned and function best with opaque/matte light coloured surfaces that reflect the light optimally [1]. The OSS system in this study allows for change in exposure time to be able to capture surface information from varying skin tones. However, dark surfaces might reduce the accuracy [1], and therefore, since we have patients of all skin colours, we found it important to investigate the accuracy of both fair and dark skin colours. Hence, an important result of this study was that, regardless of the fair or dark colour of the phantom, the surface imaging showed preserved accuracy. This has, to our knowledge, previously not been investigated for the EXTD system.
Improved accuracy was observed for the surface imaging compared to the planar x-rays in yaw and pitch. For surface imaging, these results imply that both phantoms had sufficient topography for the OSS system. Even though a full 3D surface is not acquired when using a single-camera configuration (see figure 5), the high resolution of the system collects enough data points to accurately calculate the rotations investigated in this study. Also, the DICOM reference surface generated from the planning CT might impact the SGRT accuracy [1, 2], however, strong topography, as the nose and forehead structures, was adequately reconstructed. Figure 6 shows the topography that the surface imaging system uses for localisation, and the internal structures in the orthogonal x-ray images used for calculations. Based on the results in this study it seems that the topography captured by the OSS system provides increased information about the rotations in yaw and pitch compared to the bony anatomy in the planar, orthogonal x-ray images.
One limiting factor of this study was that the CT scan was acquired in 2 mm slices, twice the thickness of the CBCT slices (see table 1). This might have affected the accuracy of the CBCT match and therefore affected the comparison of the proposed shifts of the different systems. The measurements were only performed once for each angle, and only nine angles were investigated. For more comprehensive results, more angles could have been investigated and measurements repeated over time.

One main challenge, when using surface guided radiotherapy for whole brain radiotherapy, is the obstruction of the patients surface by the traditional fully covering immobilisation mask. Hence, all patients in this study were immobilised in an open-faced mask. Overall, clinically small intrafractional motion was observed for the vector of translations (median 0.3 mm, range 0.0-1.3 mm) detected by the OSS system. The maximum shift observed was 1.1 mm in the longitudinal direction and the maximum rotational shift was 0.8 degrees in the pitch direction. These results show that the open-faced mask is an adequate immobilisation for WBRT. The WBRT treatment plan includes margins of 5 mm around the target structure and the motion detected within this study is well within these margins. The maximum effect on the D98% by the largest motion for each patient resulted in a 0.7% dose deviation. However, the dose calculation on the uncertainty plans assumes that the deviation in patient position occurs throughout treatment, at every fraction, and, since the maximum motion detected only occurs for a short time during one fraction, the actual dosimetric effect on the treatment for these patients is negligible.
Reitz et al recently published a study of intrafractional motion in four different mask system [14]. For the two different open masks in their study, they found a median vector deviation of 0.3 mm and maximum deviations of 0.6 mm and 0.6 degrees for translational and rotational movement, respectively. The median vector deviation and the maximum rotational shift found in this study are similar to the results of Reitz et al, while we found a slightly larger maximum translational shift. Li et al also investigated open masks, and concluded that they could provide immobilisation within 2 mm [15] which is fairly similar to our results with a maximum of 1.3 mm. Compared to the results found by Zhou et al [17] we found smaller maximum intrafractional motion in our patients (maximum translational and rotational shifts of 1.1 mm and 0.8 degrees compared to their 2.5 mm and 1.4 degrees). However, Zhou et al found median shifts between 0.1-0.4 mm and 0.1-0.2 degrees, while this study found median shifts of 0.1-0.2 mm and 0.1 degrees, which fairly similar results. Another study of the immobilisation capabilities of open mask conducted by Wiant et al found a maximum vector deviation of 3.5 mm [16], contrary to our maximum of 1.3 mm. This difference could be due to the larger patient cohort in the study of Wiant et al (22 patients) and the fact that they investigated open masks for head and neck cancer patients, while we investigated them for WBRT patients. Based on the results in this study, and previous publications summarised in this report [14–17] an intrafractional motion beam-hold threshold could be estimated using the values for the 95% confidence interval, which would be around 1 mm. This would result in beam-hold for every 20th treatment session and would be detected in real-time with submillimeter accuracy using surface imaging. Even though, WBRT does not require intrafractional motion management within 1 mm, this study opens for using surface imaging in combination with open-faced mask for other more high-precision treatments as well.

6 Conclusion

For the two head phantoms, excellent agreement was observed for both x-ray and surface imaging compared to CBCT. The maximum difference observed was 0.4 degrees, which fulfills the QA guidelines published by ESTRO-ACROP and AAPM TG-302 [1, 2].
The EXTD system's accuracy showed no dependence on the optical characteristics of the fair- and dark-coloured phantoms used in this study.

For all patients included in this study, the surface guidance real time tracking of the patient's rigid face structures can detect submillimeter patient motion and in combination with its beam hold capabilities, deliver a high-accuracy treatment in the open face masks. Open masks can therefore be implemented for all WBRT patients in the clinic. Additionally, since the maximum motion detected was 1.3 mm and 95% of the motion was within 0.7 mm, it could be possible to lower the surface beam-hold tolerance, which today is at 2.5 mm for the translation vector. Open-faced masks provide a precise immobilisation and can further be investigated as an alternative to full-face masks for other patient groups.

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