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Optical surface scanning of breast cancer patients in radiotherapy - an investigation of inter- and intrafractional motion effects

Annika Mannerberg

Supervision

Sofie Ceberg, Malin Kügele, Lovisa Bergh, Anneli Edvardsson och Sara Alkner, Lund

Department of Medical Radiation Physics,
Clinical Sciences, Lund
Lund University
www.msf.lu.se

Förbättrad positionering av bröstcancerpatienter som genomgår strålbehandling

Cirka 30 000 kvinnor får diagnosen cancer varje år i Sverige [1]. Av dessa utgör bröstcancer den vanligaste diagnosen med över 9000 fall per år [2]. Cancern kan vara begränsad till endast bröstet, men kan också ha spridit sig till de intilliggande lymfkörtlarna. Behandling av bröstcancer med körtelengagemang inleds vanligtvis med kirurgi och därefter är det vanligt att patienten även får strålbehandling. Syftet med detta är att, med hjälp av strålningen, eliminera de tumörceller som fortfarande kan finnas kvar efter operationen och på så sätt minska risken för att en ny tumör börjar växa. På Skånes Universitetssjukhus i Lund delas strålbehandlingen för bröstcancerpatienter med körtelengagemang upp på 25 fraktioner. Patienten får en lika stor stråldos vid varje behandlingstillfälle.

Innan strålbehandlingen påbörjas genomgår patienten datortomografi., som genom röntgenteknik genererar snittbilder av patienten. Vid detta tillfälle positioneras patienten i en fixation som ska användas under alla kommande behandlingstillfällen. Fixationen säkerställer att patienten ligger still och likadant under hela behandlingen. Utifrån datortomografin görs sedan en stråldosplan, i vilken man bestämmer hur strålningen ska ges och med vilka maskininställningar.

Vid strålbehandling är det viktigt att endast tumörområdet bestrålas och att den friska vävnaden skonas i så stor utsträckning som möjligt. En viktig del för att uppnå detta utgörs av att patienten ligger korrekt positionerad varje dag vid behandlingen. Det konventionella sättet att positionera patienten inför behandling är att använda sig av ett laserbaserat koordinatsystem som finns inne i behandlingsrummet samt markeringar som ritas på patientens hud vid datortomografin. När laser och hudmarkeringar sammanfaller antar man att patienten är korrekt positionerad. För att verifiera patientens position tas röntgenbilder på patienten innan behandlingen startas. Detta görs de tre första fraktionerna och därefter en gång i veckan. Röntgenbilderna matchas mot referensbilder från CT-skanningen och när dessa bilder överlappar vet man att patienten kommer få sin behandling till rätt område. De dagar som verifikationsbilder inte tas, positionerar man patienten endast utifrån laser och hudmarkeringar. Trots att patienten är fixerad finns det utrymme för rörelse. Patientrörelser kan påverka tumörområdets position, utan att detta kan upptäckas med laser och hudmarkeringar. För bröstcancerpatienter påverkas bestrålningsvolymens position exempelvis av armens position, som är placerad ovanför huvudet. Eftersom inga hudmarkeringar ritas på patientens armar finns det risk för att en sådan felpositionering inte upptäcks och patienten får inte den stråldos till den volym som var planerat.

För att förbättra patientpositioneringen under strålbehandling har optiskt ytskanning utvecklats, vilket bygger på att synligt ljus skannar av en vald volym av patientens yta medan hen ligger på britsen. Med hjälp av det reflekterade ljuset från patienten kan systemet beräkna patientens position i rummet och därmed upptäcka en eventuell felpositionering av patienten. Ljuset som patienten skannas med är vanligt, synligt ljus och ger därför ingen extra stråldos. Eftersom det är en hel volym av patienten som skannas kan exempelvis felpositionerade armar hos bröstcancerpatienter upptäckas och justeras.

I detta examensarbete undersöktes om patientpositioneringen av bröstcancerpatienter med körtelengagemang kunde förbättras genom att positionera patienterna med ett optiskt ytskanningssystem. Studien genomfördes genom att patienter positionerades med detta optiska ytskanningssystem, istället för med laser och hudmarkeringar. För alla fraktioner där röntgenbilder togs noterades avvikelsen mellan dagens bild och referensbilden. Dessa siffror jämfördes därefter med motsvarande siffror från patienter som hade lagts upp med hjälp av laser och hudmarkeringar för att undersöka om optisk ytskanning bidrog till mindre avvikelser i positioneringen.

Studiens resultat visar på en förbättring av patientpositioneringen då optisk ytskanning används. Detta innebär att patienten kan positioneras med en god noggrannhet även de dagar då verifikationsbilder inte tas, utan att erhålla någon extra stråldos från röntgenbildtagning. Med hjälp av bättre daglig patientpositionering får patienten även en bättre behandling eftersom rätt volym blir bestrålad.

Abstract

Purpose: The overall purpose of this master thesis was to investigate if the patient positioning could be improved for breast cancer patients with nodal involvement, using the optical scanning system Catalyst during patient setup. Patient motion during treatment and the effect it has on the dose distribution was also investigated.

Materials and Methods: Eleven patients positioned according to the Catalyst and 10 patients positioned according to the conventional laser and skin markings based setup (LBS) were enrolled in this study. To evaluate if positioning was improved with the surface based setup (SBS), the setup deviations arising from matching daily verification images to the reference images were acquired for both positioning methods. The setup deviations were then compared between the different methods by studying the distribution of deviations. The systematic and random setup deviations and PTV margin were also determined for both groups. In total, 127 fractions of patients positioned with LBS and 93 fractions of patients positioned with SBS were analysed. To investigate what impact the offline correction strategy used at Skåne University Hospital (SUS) has on the positioning, the data was analysed both with and without the offline corrections applied.

The dosimetric effect of patient motion was evaluated for one patient by analysing recorded motion data during beam delivery by the Catalyst system in terms of isocenter shift. All isocenter shifts that occurred when the beam was on were extracted and added to the original patient position to get the total isocenter shift, including both inter- and intrafractional motion. The mean isocenter shift for each fraction was determined and the isocenter position was shifted in the original treatment plan for each fraction in the treatment planning system (TPS). The dose was then re-calculated for each fraction and summed to one plan that was compared to the original dose distribution.

Results: The obtained results indicate that SBS is a better method of positioning patients than LBS. For LBS, with offline corrections included, the amount of fractions where setup deviation exceeded the clinical setup deviation threshold of 4 mm was 22% / 21% / 28% in vrt/lng/lat. The corresponding values for SBS were 7.5% / 6.5% / 20% in vrt/lng/lat. The systematic and random setup error was smaller with Catalyst setup in all directions and the PTV margin could be reduced in the lng direction for SBS, compared to LBS.

The setup deviations were also evaluated for LBS and SBS, both with and without the offline corrections applied. The results showed that although it is important to use the correction strategy for LBS, SBS did not depend on the correction strategy and the positioning was not improved as much for this method.

No large impact on the DVH could be seen for the PTV of the summed treatment plan where the isocenter was shifted to a mean position for each fraction. $D_{98\%}$ of the original plan was 46.6 Gy. $D_{98\%}$ for the plan where the isocenter was shifted was 46.5 Gy. The absorbed dose to the heart and left lung was lower than in the original plan and the absorbed dose to the spinal cord was slightly increased. The difference between the plans was not clinically relevant.

Conclusions: The amount of setup deviations exceeding 4 mm was decreased in all directions for SBS compared to LBS. Also, both the systematic and random setup error was decreased for SBS. The correction strategy improved the positioning for LBS, while the SBS did not depend as much on the corrections. The DVH of one patient with considerable motion during treatment indicated that the dose distribution was not affected to any large extent, when inter- and intrafractional motion was considered. However, to be able to draw any definite conclusions about the dosimetric effect due to patient motion more patients have to be evaluated.

Abbreviations

AML	Adaptive Most Likelihood
CBCT	Cone Beam Computed Tomography
CTV	Clinical Target Volume
DRR	Digitally Reconstructed Radiograph
DVH	Dose Volume Histogram
LAT	Lateral
LBS	Laser/skin markings Based Setup
LNG	Longitudinal
MVCT	Mega Voltage Computed Tomography
NAL	No Action Level
OAR	Organs at Risk
PTV	Planning Target Volume
ROT	Rotation
SBS	Surface Based Setup
TPS	Treatment Planning System
VRT	Vertical

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1. Introduction

More than 60 000 people are diagnosed with cancer every year in Sweden [2]. Half of these are at some point treated with radiotherapy [3]. Radiotherapy aims to irradiate a target volume, with a high radiation dose, while sparing the surrounding healthy tissue as much as possible. To achieve the best treatment results the patient must be positioned correctly, according to the planning CT, and in the same way during all treatment sessions. Another factor that can affect the outcome of radiotherapy is intra- and interfractional patient motion during the treatment course. Intrafractional motion is patient motion that occurs during a treatment session. Such motion is due to, for instance, respiration, swallowing or gastrointestinal motion. Interfractional motion is the patient related difference that occurs from one treatment session to another. These differences can, for example, be caused by weight gain or loss, variance in the filling of the bladder or different patient position between treatment sessions. Without good accuracy in the radiation delivery, there is a risk of not covering the target volume and instead deliver radiation to normal tissue. This can lead to radiation induced cancer or that the patient is not cured [4].

During delineation of the tumour and organs at risk (OAR) the physician delineates the clinical target volume (CTV) which is the tumour site with margins for microscopic cancer cells. Since, for instance, patient breathing motion and day-to-day variability in patient setup is inevitable, a margin to the CTV is added to account for deviations in patient positioning. The new volume is called planning target volume (PTV) and is the volume to be irradiated [5].

The conventional way of positioning the patients is to use a laser based coordinate system and external skin markings. When the patient is positioned so that the lasers and markings align, it is assumed that the PTV is in the correct position. To avoid patient motion during treatment, the patients are positioned in a fixation system. The choice of fixation depends, amongst other things, on the target and what best ensures that the patient can lie in the same position as during the planning CT. The fixation also prevents the patient from moving for instance arms and legs during treatment.

A cause for concern regarding skin markings is that they give poor information about the location of the internal PTV. Patient motion can affect the treatment of the tumour and movements of the patient can in turn lead to displacement of the PTV, while the skin markings still align with the lasers. It is for instance of great importance for breast cancer patients that the arms and chin are positioned correctly. Arm movements can have an impact on the pendulous breast tissue, an impact which may not be detected by just examining the external markings. Although the patients are positioned in a fixation during treatment, it is still possible for them to move certain parts of their body to some degree and this can lead to displacements of the target [4].

To ensure the position of the patient imaging is performed at the start of the treatment course. These images are matched to reference images from the planning CT and if necessary, the position of the patient is adjusted by moving the couch to the correct position. The patient setup deviation is defined as the difference between the reference images and the verification images acquired prior to treatment. The setup deviation has a systematic and a random component and both affect the dose distribution to the target. Systematic deviations entail a difference between the planned and mean patient position and are present at all fractions. Random setup deviations arise due to day-to-day variations in the patient positioning and is the distribution of the patient position for every fraction around the mean position.

The number of daily images that is acquired during the whole treatment course depends on for instance number of fractions and fraction dose. At SUS, for patients without fiducial markers whose treatment consists of a fraction dose below 7 Gy and more than 5 treatment sessions, images are acquired the first three fractions and once a week after that. After the first three fractions the size of the systematic deviation is estimated and is corrected for if necessary the following fractions throughout the treatment. With subsequent, continuous imaging, systematic setup deviations can be discovered during the rest of

the treatment course. During the fractions without imaging the patient is positioned according to the laser and skin markings only.

With evolving radiotherapy techniques, optical surface scanning imaging has been developed to improve the positioning of patients undergoing radiotherapy. At SUS the optical surface scanning system used is the Catalyst (C-Rad Positioning AB). The Catalyst uses nonionizing radiation to compare a reference surface of the patient from the CT with a live surface in the treatment room, and detect deviations between these different surfaces. Optical surface scanning can thus ensure that the total scanned volume is in the same position as in the reference situation. Furthermore, the Catalyst uses optical triangulation and a non-rigid algorithm to calculate where the isocenter in the PTV is located. During treatment the Catalyst can be used for motion monitoring, displaying how much the current isocenter position deviates from the planned position. If the patient motion exceeds the predetermined limits, the beam can be interrupted and the patient's position can be re-adjusted.

It has been shown that patient setup can be improved with surface scanning [4], [6–12]. The use of surface scanning can decrease setup deviations without delivering any additional radiation dose to the patient.

At the radiotherapy department at SUS in Lund, breast cancer patients with nodal involvement are normally positioned with lasers and skin markings. This positioning method is initiated with placing a small lead marker in the middle of the patient's thorax before the planning CT scan. The patient is also given a tattoo at the site of the lead marker. The marker is visible on the CT images and is an external reference point. The location of the internal isocenter in the target volume is set during the dose planning and the distance between the external reference point and the internal isocenter is determined in the vrt, lng and lat direction in the TPS. During the first treatment session, the patient is initially positioned with the laser and tattoo aligning. The treatment personnel then move the couch the predetermined distance in the vrt, lng and lat direction to obtain the isocenter in the correct position. External skin markings are after this drawn on the patient at the site of the laser to mark the correct treatment position in vrt, lng and lat.

To verify the patient positioning, two orthogonal setup x-ray images and one setup field image is acquired the first three fractions and after that once a week. The images are matched to the digitally reconstructed radiograph (DRR) reference image from the planning CT, with respect to the bony anatomy. The frontal image is matched in the lat direction with respect to the inner part of the rib cage including the vertebrae. In the lng direction, the frontal image is matched with respect to the medial parts of the clavicle. The orthogonal image, taken from the side, is matched with respect to the sternum in the vrt direction. The field image ensures that the breast is within the field.

Kügele *et al.* [6] has shown that the positioning of breast cancer patients without nodal involvement, treated with tangential fields, is improved when the patients are positioned using the Catalyst, and as a result of this study this patient group is today positioned with the Catalyst only at SUS.

Crop *et al.* [7] compared patient setup between positioning with Catalyst and laser by examining the difference between initial positioning and final position after imaging with mega voltage computed tomography (MVCT). The study involved breast cancer patients with nodal involvement treated with Tomotherapy. The study showed that patient positioning with Catalyst was more precise than laser positioning. The results also indicated that Catalyst can provide an accuracy in patient setup equal to MVCT for breast cancer patients.

Stieler *et al.*[12] evaluated the calculated isocenter position by Catalyst compared to matching a cone beam computed tomography (CBCT) to the planned isocenter position. The study showed a good agreement between the Catalyst and CBCT and indicated good accuracy for the isocentric calculation performed by Catalyst. At the time of the study by Stieler *et al.* Catalyst used a rigid algorithm for surface matching. These authors noted that an elastic algorithm was likely to provide an even better accuracy for patient setup using Catalyst [12].

During this study, the position of the isocenter was determined utilizing a novel non-rigid algorithm that includes information about the whole PTV volume when calculating the position of the isocenter. This algorithm is an option in the Catalyst system and provides a more solid calculation of the isocenter position.

1.1 Aim

The aim of this master thesis was to evaluate if the patient positioning could be improved for breast cancer patients with lymph node involvement, by positioning the patients according to the optical surface scanning system Catalyst (C-Rad Positioning AB) during setup using the novel PTV-based algorithm, compared to the conventional laser/skin markings based setup.

An additional aim was to evaluate the dosimetric effects of potential isocenter shift due to inter- and intrafractional motion of the patient.

Questions to be answered were:

- Can the positioning of breast cancer patients with lymph node involvement be improved using the optical surface scanning system Catalyst during patient setup?
- To what extent is the dose distribution affected by the patient's potential movements during beam on?

2. Theory

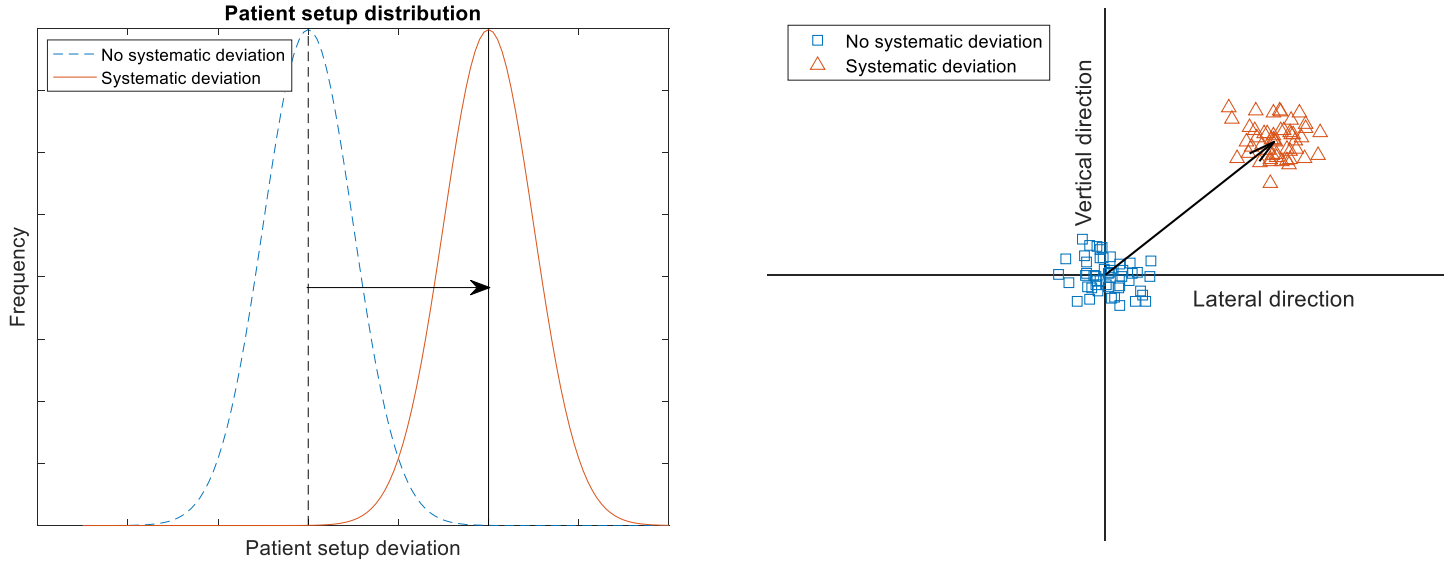
2.1 Patient Setup Deviations

A patient setup deviation occurs when there is a difference between the intended volume to be irradiated and the actual volume that is irradiated. The deviations can be measured by registering the difference between the DRR from the CT scan and the daily verification image.

Patient setup deviation can be divided into systematic and random deviations. A systematic deviation cause a difference between the mean patient position and the planned patient position. Systematic deviations are associated with treatment preparation variations and are present at all fractions. A systematic deviation can for instance be introduced from tumour delineation variability. Random setup deviations describe the distribution of the patient position around the mean position. Since random deviations correspond to the day-to-day setup variations, these deviations vary between different fractions and can for example arise from organ motion [13].

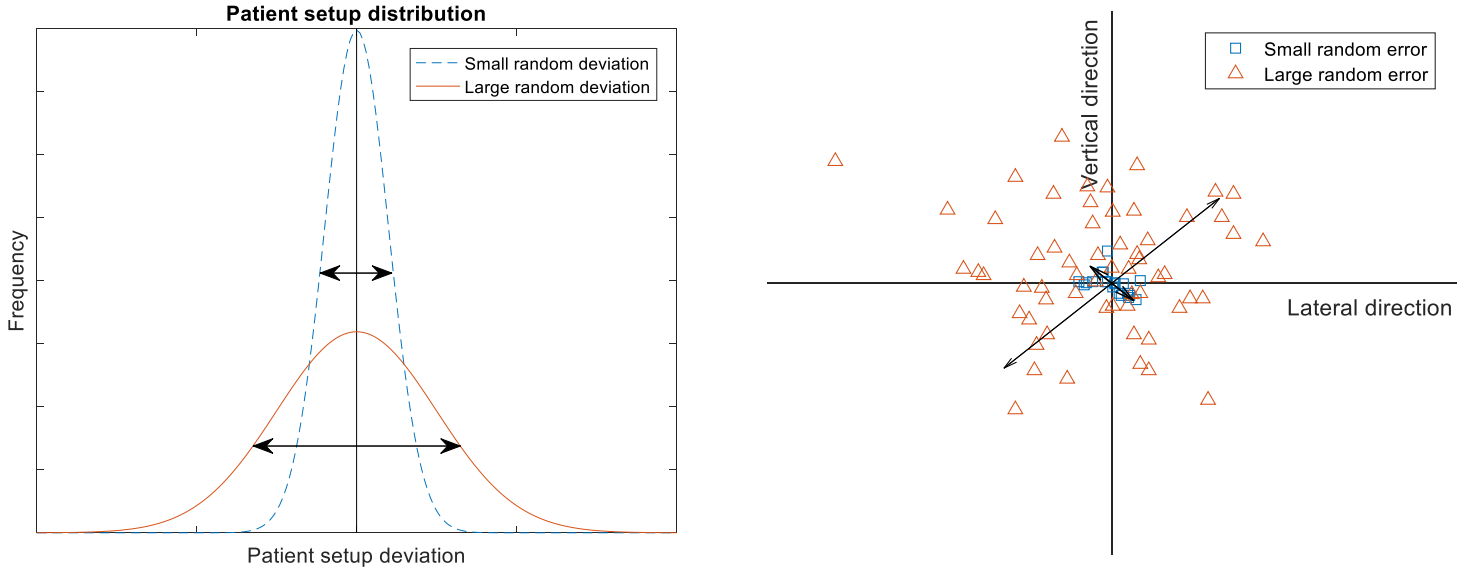
Both systematic and random deviations have an impact on the delivered dose to the target and the OAR. The systematic deviations lead to a shift of the dose distribution from the planned target position. Since the random deviations differs from day to day, these errors cause the dose distribution to be blurred. The systematic and random deviations need to be taken into account when the PTV margin for the CTV is determined [14]. Illustrations of systematic and random setup deviations can be seen in Figure 1 and Figure 2. The appearance and position of the dose distribution can be correlated to the distribution of the patient position displayed in the figures. Figure 1 shows how the treatment is affected by a systematic setup deviation. The mean patient position is shifted, and although the patient is positioned with high precision at every fraction, the systematic deviation will still cause a difference between the intended and actual treated volume throughout the whole treatment. Figure 2 demonstrates how random deviations influence the distribution of the patient position; with a larger random deviation, more blurring of the dose distribution will arise. It can also be noted that for both good and poor precision in daily patient setup, the mean patient position can be the same.

Random deviations are best prevented by using good immobilization equipment and to ensure that the patient setup is reproducible. In order to avoid systematic deviations a correction strategy should be used [15].



(a) (b)

Figure 1. Mean patient position shift introduced by a systematic deviation in one direction (a) and two directions (b). The dashed, black vertical line in (a) corresponds to the mean patient position if there was no systematic setup deviation present, whereas the solid, black line represents the resulting mean patient position from a systematic deviation. Each square and triangle in (b) is equivalent to a measurement of the patient position for one fraction, where the origin corresponds to the planned position. The arrows illustrate the direction and size of the systematic deviation.



(a) (b)

Figure 2. How the patient setup distribution is affected when random deviations of different size are introduced, illustrated in one (a) and two (b) directions. The black, vertical line in (a) represent the mean patient position around which the random deviations are distributed. Every square and triangle in (b) correspond to one patient setup position, and they are all distributed around the same mean; the origin. The arrows illustrate the size of the random deviation.

2.1.1 Determination of Systematic and Random Errors

To be able to separate systematic from random deviations by examining the difference between the DRR and the verification x-ray images, several images need to be taken for every patient. The accuracy of the analysis of the systematic and random deviations depends on the number of patients, *P*, and the number of images, *N*, acquired [16].

Eq. 1-6 describe how to determine the systematic, Σ, and random, σ, setup error and if the overall mean systematic deviation is statistically significant. In Table 1 explanations to the notations used in Eq. 1-6 can be seen.

Table 1. Explanations to the notations used in Eq. 1-6.

Symbol	Explanation
i	Image number
p	Patient number
$\mu_{DRR-setup}$	Deviation between the DRR and the setup image in a given direction
n_p	Number of images acquired for patient p
N	Total number of images included in the study
P	Total number of patients included in the study
m_p	Mean position deviation for patient p, i.e. the individual systematic deviation for patient p in a given direction
m_o	Overall mean systematic deviation in a given direction, i.e. the mean of m_p for all patients P
σ_p	The standard deviation of the distribution of $\mu_{\mathrm{DRR-setup}}$ for patient p in a given direction, i.e. the individual random setup deviation
σ	The standard deviation of the distribution of σ_p, i.e. the random setup error for all patients P in a given direction
Σ	The standard deviation of the distribution of m_p, i.e. the systematic setup error for all patients P in a given direction

The individual systematic error, m_p, is defined as the mean of all measured deviations between the DRR and the setup images, $\mu_{DRR-setup}$, for one patient, in a given direction, according to Eq. 1. An individual systematic deviation could for instance arise from a misplaced skin tattoo.

$$m_p = \frac{1}{n_p}\sum_{i=1}^{n_p}\mu_{(DRR-setup)i} \tag{1}$$

The individual random deviation, σ_p, is the standard deviation of the $\mu_{DRR\text{-}setup}$-distribution for one patient and can be determined according to Eq. 2.

$$\sigma_p = \sqrt{\frac{1}{n_p - 1}\sum_{i=1}^{n_p}\left(\mu_{(DRR-setup)i} - m_p\right)^2} \tag{2}$$

The overall mean systematic deviation, m_o, for all patients is defined as the mean of m_p and is defined as

$$m_o = \frac{1}{N}\sum_{p=1}^{P} n_p \cdot m_p \tag{3}$$

It follows from Eq. 3 that m_o is the mean that the values of m_p are distributed around and that the equation takes the number of images acquired for every patient into account. Whether m_o is statistically significantly nonzero, can be determined accordingly [17]:

$$|m_o| > t \cdot \frac{\Sigma}{\sqrt{P}} \tag{4}$$

where t is the constant of the t-distribution for $P-1$ degrees of freedom at the 95 % confidence level. If m_o is statistically significant, there is a systematic deviation that affects all patients. This could for example be a misaligned laser in the treatment room.

For a patient population, the systematic error, Σ, which is the standard deviation of m_p, can be determined by Eq 5.

$$\Sigma = \sqrt{\frac{P}{N(P-1)} \sum_{p=1}^{P} n_p (m_p - m_o)^2} \tag{5}$$

The random setup error for the whole patient population, σ, is the standard deviation of the distribution of the individual random deviations, see Eq. 6.

$$\sigma = \sqrt{\frac{1}{N-P} \sum_{p=1}^{P} \sigma_p^2 \left(n_p - 1\right)} \tag{6}$$

2.1.2 Patient Setup Correction Strategy

At SUS the strategy used to correct for systematic deviations is No Action Level (NAL) in combination with the Adaptive Most Likelihood (AML) strategy [17]. According to Månsson *et al.* [17] this is the optimal correction strategy to be used at SUS.

For the NAL strategy, setup images are acquired during the first n_p fractions and thereafter the mean setup deviation for these first fractions is determined. The patient position is then corrected according to the calculated mean deviation for the following fractions [18].

The AML strategy is based on a correction factor, k, which takes the systematic and random setup errors into account during the calculation, according to Eq. 7, where n is the number of images [16].

$$k = \frac{n\Sigma^2}{n\Sigma^2 + \sigma^2} \tag{7}$$

According to Månsson *et al.* [17] the systematic and random setup deviations are approximately equal, and therefore the correction factor used at SUS is instead the one seen in Eq. 8.

$$k_{SUS} = \frac{n}{n+1} \tag{8}$$

For breast cancer patients with nodal involvement which are treated at SUS, setup images are acquired during three first fractions. The mean displacement is then calculated in the vrt, lng and lat direction and multiplied with the correction factor k_{SUS}. If the result is equal to or greater than the permanent correction level a permanent correction of the patient position is performed (Table 2).

If, during the first three fractions, $\mu_{DRR-setup}$ is equal to or larger than 5 mm an online position correction is done. From fraction 4 and onwards the acute action level is instead 4 mm, see Table 2. After the third fraction setup images are acquired once a week. In the case of $\mu_{DRR-setup}$ being equal to

or larger than 4 mm after the third fraction, an online correction is performed and setup images are acquired during the following fraction as well. The correction strategy is then applied on the result from these two fractions to determine if a permanent position correction should be done.

Table 2. The imaging modality, imaging protocol and action levels for breast cancer patients with nodal involvement, treated with radiotherapy, at SUS.

Imaging modality	Acute action level, fraction 1-3 [mm]	Acute action level, fraction 4-25 [mm]	Action level, permanent correction [mm]	Imaging protocol
Elekta: Setup MV/MV + field MV Varian: Setup kV/kV + field MV	5	4	3	Fraction 1-3 + 1/week

2.1.3 Determination of PTV-margin

Since both systematic and random deviations affects the dose distribution, a margin must be added to the CTV to account for the deviations. The new volume is the PTV and the distance between the PTV and CTV is called the PTV margin. M van Herk *et al.* [14] analysed how much the dose distribution is affected by systematic and random deviations and developed a recipe for how to determine the appropriate PTV margin, see Eq. 9.

$$\mathrm{PTV}_m = 2.5\Sigma + 0.7\sigma \tag{9}$$

Eq. 9 applies for a 95 % dose coverage to the CTV, for 90 % of the patients.

2.2 The Optical Surface Scanning System

The optical surface scanning system Catalyst is a system used within radiotherapy for patient positioning and monitoring. The system utilizes optical surface scanning in order to determine the position and movements of the patient before and during treatment sessions. The Catalyst unit, mounted on the ceiling, consists of a LED projecting visible light on the patient and a camera detecting the reflected light from the patient. With the information from the reflected light the system can calculate the distance to the object and create a 3D surface using optical triangulation [19]. The Catalyst can also estimate the position of the isocenter relative to a reference using a non-rigid algorithm [20].

Both three unit systems (Catalyst HD) and single unit systems exist. With three cameras, the system can scan up to 200 scans/s and the patient positioning and motion detection accuracy is within 0.5 mm. For the one camera system, the scan speed is 80 scans/s and the accuracy for both patient positioning and motion detection is within 1 mm. Both systems can scan a volume size of 800 mm x 1300 mm x 700 mm in the lateral (lat), longitudinal (lng) and vertical (vrt) direction [21], [22].

When importing a patient to the Catalyst system an appropriate template is chosen which determines the tolerance for isocenter shift and surface shift. These tolerances can also be set manually if needed. During the Catalyst import the size of volume to be scanned is defined. The skin rendering structure from the CT scan is included during the patient import and this structure forms the reference surface for the patient positioning. If the patient is re-positioned at some point during the course of treatment, a new reference image can be acquired in the Catalyst system.

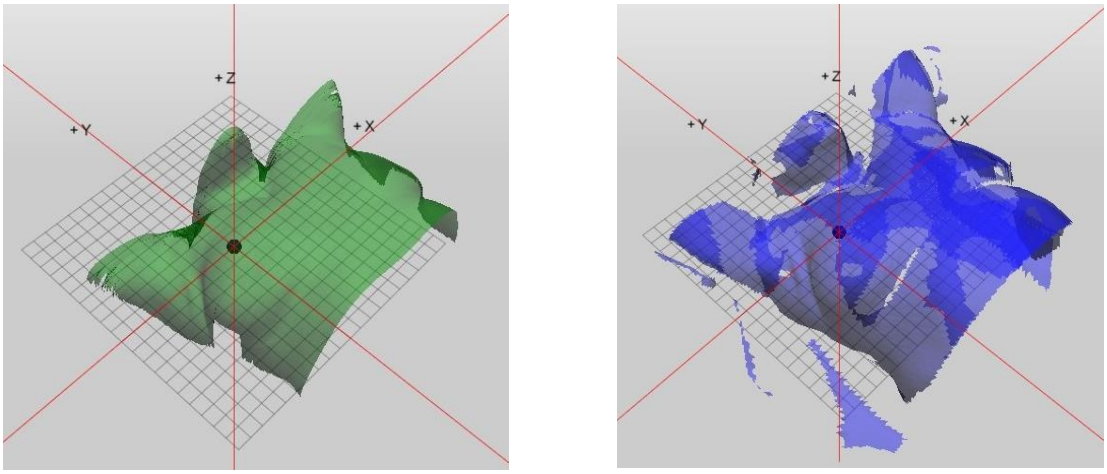
The Catalyst can be used for positioning the patient in the cPosition-mode and monitor the patient's movements during treatment in the cMotion-mode. The Catalyst can also be used for respiratory gated treatments in the cRespiration-mode, however this mode was not used in this study and will therefore not be further explained.

2.2.1 Patient Positioning

In the application cPosition, the system analyses the amount of deviation for a live surface relative to the reference surface. The live surface is generated through the reflection of the projected light ($\lambda = 405$ nm) on the patient and is updated continuously [21]. If the scanned volume results in a poor live surface with loss of signal in several parts of the surface, the settings "Time" and "Gain" can be adjusted. Time represents the exposure time and gain is the saturation.

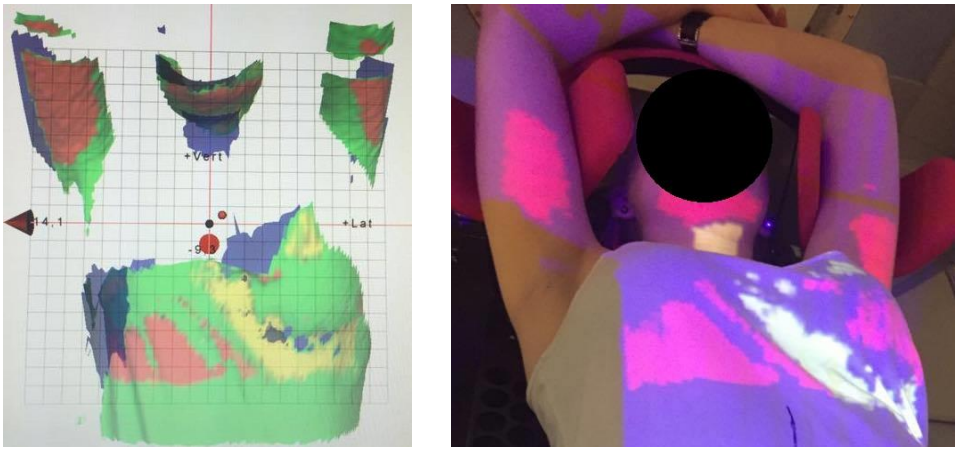
The live and reference surfaces and the calculated isocenter shift can both be seen on the Catalyst computer screen in the treatment room. Figure 3 shows an example of a reference and live surface.

Deviations between the live surface and the reference surface exceeding the tolerance level will be displayed as different colours projected on to the patient's surface, depending on how the patient is displaced. A green light ($\lambda = 528$ nm) indicates that the patient is positioned too low and a red light ($\lambda = 624$ nm) indicates that the patient is positioned too high, in comparison with the reference surface, see Figure 4 [21]. By using the projected colour map, any patient rotation can also be detected. The patient position should be adjusted according to the projected colourmap so that the live and reference surfaces align. Once the surfaces are aligned within the pre-set tolerance level, the projected light turns transparent.



(a) (b)

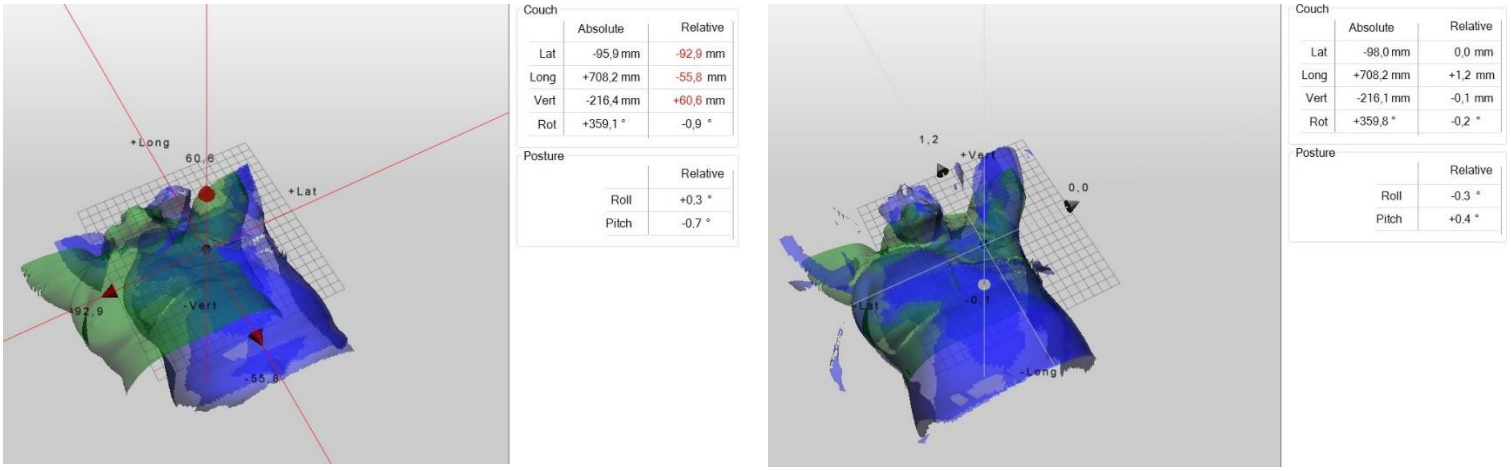
Figure 3. Example of a reference surface (a) and live surface (b) in the Catalyst system.



(a) (b)

Figure 4. The resulting colormap when the reference and live surfaces are not aligned, shown on the Catalyst display in the treatment room (a) and projected on to the surface of a patient (b).

When the calculated isocenter of the live surface differs from the reference isocenter more than the set template, the numbers on the Catalyst screen will appear red. These numbers instruct the treatment personnel how much and in what direction the patient should be moved to enable the calculated isocenter to coincide with the reference isocenter. Once the real-time calculated isocenter is in the correct position, the numbers on the display will cease being red. The isocenter shift is calculated in 6 degrees of freedom; vrt, lng, lat, rotation (rot), roll and pitch. Figure 5 shows an illustration of how a patient displacement results in red numbers and how it looks once the patient is in the correct position.



(a) (b)

Figure 5. Deviation between the reference and live surface resulting in red numbers (a) and the reference and live surface aligned (b).

2.2.2 Patient Motion Monitoring

After the patient has been placed in the correct treatment position, the cMotion-mode can be entered. In this mode, the patient's movements can be monitored during the treatment delivery. When entering cMotion, the live surface from cPosition becomes the reference surface for that specific monitoring. The Catalyst continuously monitors if the patient moves relative to the position determined during patient setup. The calculated motion induced isocenter shift are displayed as bars in a diagram (Figure 6). The isocenter shift displayed represent the length of the vector combining the deviations in the vrt, lng and lat direction. If the patient moves in a way that leads to an isocenter vector shift exceeding the tolerance level the green bars in the diagram become red. The beam can then be interrupted and the patient's position adjusted back to the correct position. The interruption of the beam can be installed to be automatic. If the beam interruption is not automatic, the beam must be stopped manually. This means that even though the movements of the patient cause an isocenter vector shift exceeding the tolerance level, it is possible to continue irradiating the patient. This possibility can be seen in Figure 6, where the treatment has been carried out despite the occasional large patient motion.

Every isocenter shift that is registered in cMotion is saved and can be analyzed. The information saved include elapsed time and shifts in the lat, lng and vrt direction and the rot, pitch and roll of the patient. The isocenter shift vector and if the beam was on or off is also registered.

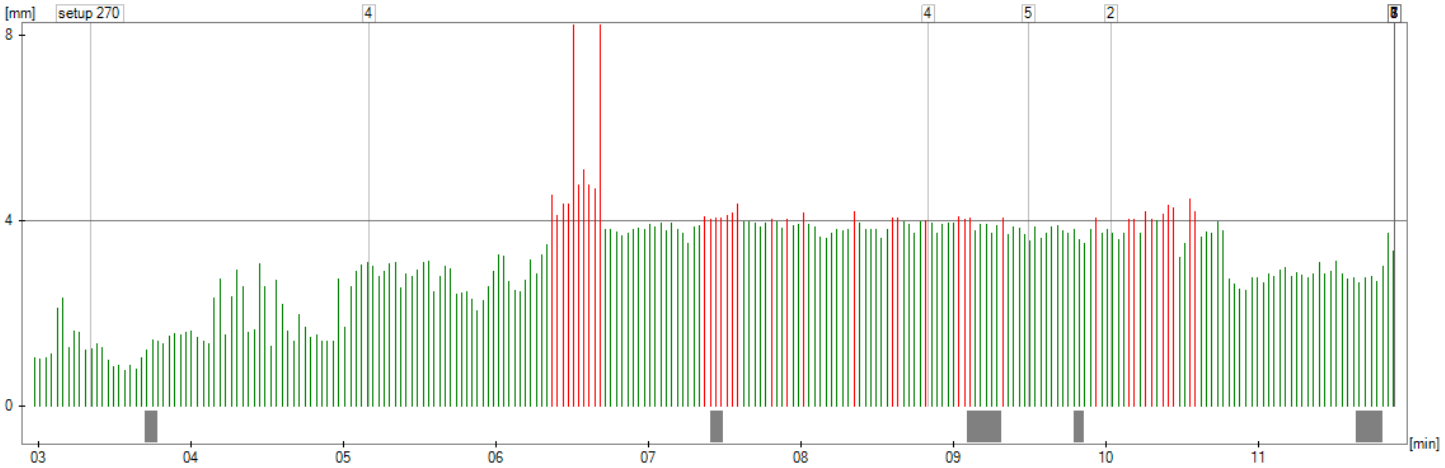


Figure 6. An example of a diagram resulting from monitoring a breast cancer patient, with nodal involvement, in cMotion. The bars show the isocenter vector shift from the reference. The red bars represent movements of the isocenter larger than 4 mm. The time displayed is the time elapsed since cMotion was entered and the grey blocks below the bars indicates beam on.

2.2.3 Isocenter Shift and PTV algorithm

The system uses a non-rigid algorithm in the calculation of the isocenter shift. A non-rigid algorithm accounts for deformations of the scanned object that have occurred between the source scan (reference surface) and the target scan (live surface) [23]. To determine the isocenter shift, the amount of deformations in the source scan must be determined first.

The Catalyst system uses optical triangulation to create a 3D triangle mesh for both the source and target scan. Both rigid and non-rigid deformations of the source can occur and these are all unknown. Therefore, the deformation of the source mesh has to be calculated, to find a deformed source scan that matches the target scan [20].

A deformation graph is created for the source scan (Figure 7). Every individual node in the graph is associated to both a linear representation and a translation and induces a deformation on the adjacent region in the graph. All nodes together therefore describe the non-rigid deformation of the scan and the graph. The rigid deformations are modelled separately and are modelled for the whole graph at once, instead of one node at a time. The rigid deformations are assigned to a rotational matrix and a translation vector, where the rotation is expressed relative to the centre of mass of the scan. The rigid and non-rigid deformations are combined in the deformation graph by first adding the local non-rigid deformations to the nodes and thereafter the global rigid transformation [20].

The source mesh deformation has to be calculated and optimised in order for the deformation graph and target scan to have a high correspondence, which means that each node in the deformation graph should have a corresponding position on the target mesh. Every node in the deformation graph is assigned an energy and the sum of these represent the global energy of the system. The purpose of the optimisation is to find the lowest energy state of the system [23]. This is an iterative process since deformations and correspondence between the deformation graph and the target mesh are unknown from the beginning [20].

The energy in each deformation graph node is a combination of weighted parameters, which include similarity to connecting nodes, distance to the corresponding point on the source and target mesh and the deviation from local rigidity [23]. The system is also assigned with a confidence energy term which weight each correspondence built on how reliable the correspondence between the deformation graph and target is. In the source scan and target scan there might be regions without any detected object. In the created meshes these regions are not empty, but instead represented by deep holes. This means that even when regions in the source mesh have no matching region on the target mesh, each node is forced

to have some correspondence to the target. In the optimisation, the weight for this correspondence becomes zero, indicating that no suitable correspondence was found. This means that regions without overlap in the source and target scan do not affect the deformation. If there was no correspondence at regions with partial overlap many artifacts would appear in the calculated deformation and the position of the isocenter would not be accurately determined [20]. An illustration of how the source scan is connected to the target scan is presented in Figure 7.

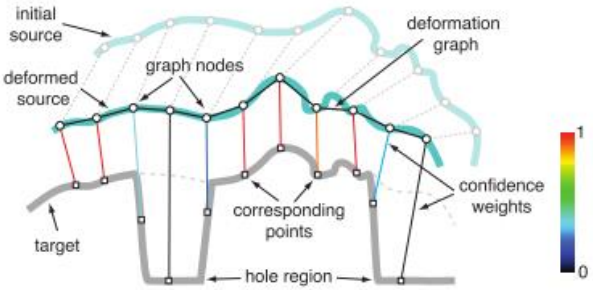


Figure 7. Illustration of the connection between the original source scan, the deformed source with its deformation graph and the target scan. The colour of the confidence weights indicates how well the correspondence between the deformation graph and the target is. [20]

When the system has reached its lowest energy state, the deformation of the source matches the target scan and the isocenter position can be determined. A volumetric mesh that consist of tetrahedrons is created, where the nodes are related to the nodes in the source mesh. To determine the isocenter position, translation and rotation in each node of the volumetric mesh are calculated. This calculation is based on the source mesh deformation and the target position [23].

The novel non-rigid PTV algorithm that can be used during the calculation of the isocenter position is based on including the centre of mass of the PTV to the calculation of the isocenter shift.

3. Materials and Methods

Twenty-one breast cancer patients with nodal involvement were included in this study and in total 220 treatment fractions were investigated. Out of the 21 patients, 10 were positioned with LBS. 11 patients were positioned with SBS. For all patients, $\mu_{DRR-setup}$was analysed for every fraction during which setup images were acquired. All patients were treated with 50 Gy in 25 fractions.

The systematic and random setup errors were then calculated for both LBS and SBS, with and without the offline corrections using Eq. 1-6. The offline corrections were extracted by calculating the mean $\mu_{DRR-setup}$ for the first three fractions and multiply this with the correct k_{SUS}. The result was then either added to or subtracted from the original $\mu_{DRR-setup}$ depending on if the correction was a negative or positive translation.

At SUS no CTV is delineated for breast cancer patients with nodal involvement. Instead the PTV is directly delineated. To get an understanding of how large a margin to a possible CTV that is needed, the PTV margin was determined by using Eq. 9.

To evaluate if there was a significant difference between LBS and SBS statistical tests were performed on the acquired setup deviation data. The absolute data in vrt, lng and lat was first tested individually with the Shapiro-Wilks test ($\alpha = 0.05$) to determine if the data was normally distributed. If not normally distributed a Wilcoxon rank sum test was performed. The analysis of absolute medians for LBS and SBS in all directions was carried out in MATLAB.

3.1 Patient Setup with Laser and Skin Markings

For LBS, the deviations between the reference and the two orthogonal kV-setup images were analysed retrospectively in Offline Review (Aria, Varian Medical Systems, Palo Alto, CA). For these 10 patients, a total of 127 fractions were studied. All patients were treated at a TrueBeam linear accelerator (Varian Medical Systems, Palo Alto, CA) and started their treatment between the 5th of July 2016 and the 7th of February 2017. For LBS, the target included the breast and the locoregional lymph nodes.

Nine patients were fixated in a Posiboard™ - 2 Breastboard (Civco Medical Solution, IA), see Figure 8, and one patient was fixated in a Wing Board™ (Civco Medical Solution, IA) with a vacuum bag placed on top.

Figure 8. Posiboard™ - 2 Breastboard (http://civcort.com/ro/breast-positioning/breastboards/posiboard2-breastboard-109030.htm)

$\mu_{DRR-setup}$ were retrieved for vrt, lng and lat directions by studying couch translations. The setup images consisted of one anterior-posterior image and one image from the right or left side, depending on target position. The coordinate system used for the setup deviations was based on the direction of the couch displacement. If the patient, and consequently the couch, had to be moved in the ventral, cranial or left direction for the DRR and setup images to match, the translation was positive. For the opposite directions, the translation was negative. The $\mu_{DRR-setup}$ values obtained from image matching by the treatment room staff were used.

3.2 Patient Setup with the Catalyst System

The 11 patients positioned with SBS started their treatment between the 27th of February 2017, and the 6th of April 2017. Of these patients, 2 were treated at a TrueBeam linear accelerator and positioned with a three-camera Catalyst system. The remaining patients were treated at an Elekta linear accelerator (Elekta AB, Stockholm, Sweden), 4 of which were positioned with a one-camera Catalyst system, and 5 with a three-camera system. For the patients positioned with SBS, a total of 93 fractions were analyzed.

For 10 of the patients, the target included the whole breast and the locoregional lymph nodes. One of the patients had been treated with radiotherapy for breast cancer before and was now given treatment to the lymph nodes only, where the cancer had relapsed.

Nine of the patients were fixated in a Posiboard™ - 2 Breastboard. One of the patients were positioned in a Standard Wing Board™, with a vacuum bag placed on top. For one of the patients a vacuum bag was placed on top of the Posiboard™ - 2 Breastboard, with the armrests removed.

When the patients were imported to the Catalyst system an appropriate template was chosen. The template has a predetermined surface offset tolerance of 5 mm. The tolerance level for the isocenter shift was set to 2.5 mm in the vrt, lng and lat direction. These thresholds were chosen because it was low enough to keep the accuracy and the staff attentive to red numbers on the Catalyst computer screen, but not too low considering the patient motion during the time between setup and imaging. During the import the setting for the PTV calculation was selected and the lower part of the stomach of the patient was cropped from the reference surface, to avoid breathing motion from affecting the positioning.

The staff was instructed to position the patients according to the Catalyst. This involved examining how well the live and reference surfaces matched and to correct for any rotation. The personnel also used the colormap to adjust the position and to verify the position of the arms and chin. The staff was then to position the patient so that the isocenter shifts were as close to zero as possible. If a bolus was used, this was placed on the patient before positioning according to the Catalyst. For every patient, the time and gain were adjusted at the first fraction to obtain the most optimal live surface. In the case of an offline position correction, the patient was positioned with the Catalyst, the couch correction was thereafter performed and a new Catalyst reference surface was acquired.

For the patients treated at a TrueBeam, the setup deviations were retrieved in Offline Review. However, the setup deviations for patients treated at an Elekta were not digitally saved, but written by hand on paper. The orthogonal setup images were not paired for the Elekta machines and therefore two values for the longitudinal setup deviation were noted. In this study, an arithmetic mean of the longitudinal setup deviation was used. If one of the setup images taken at an Elekta machine resulted in a deviation exceeding the acute action level described in Table 2, a manual online correction of the couch position was carried out. A second image was then acquired from the same direction to ensure that the patient position was correct after the online correction. Since the deviations from the first image correspond to the correct patient position according to the Catalyst, these were the values used in this study.

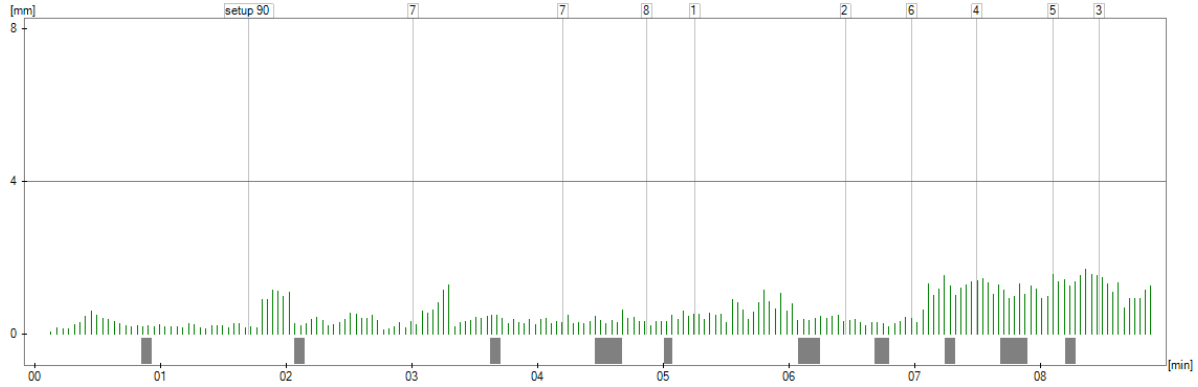
The treatment staff was asked to save the paper where the performed offline corrections were noted. With this information saved, the setup deviations without any offline corrections could be investigated with certainty of when corrections had been made.

3.2.1 Inter- and intrafractional Motion Induced Isocenter Shift

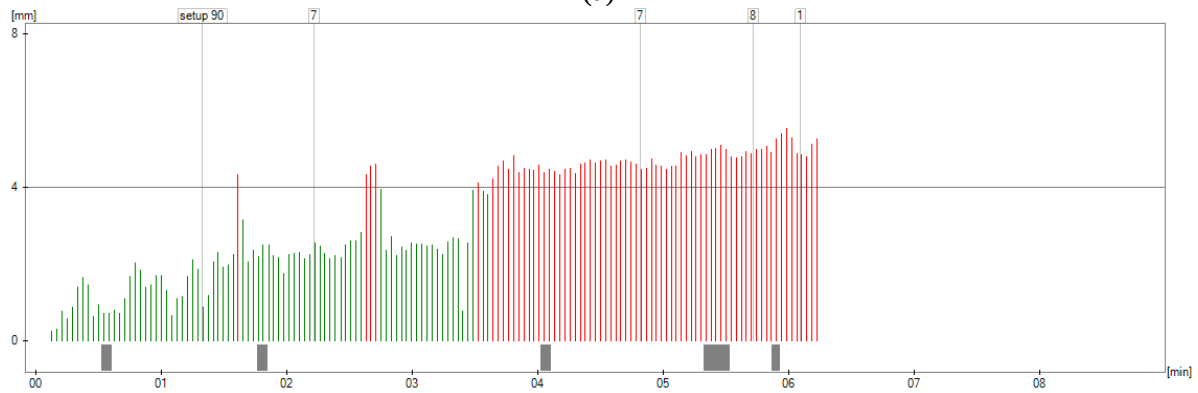
For one patient, cMotion data was extracted for all fractions where the cMotion had been used during treatment. This patient was chosen because she occasionally moved considerably during treatment and was at some treatment sessions irradiated even when her movements resulted in an isocenter shift exceeding the threshold, see Figure 9. She was treated at the left side which made it interesting to study the dose to the heart.

The bars seen in Figure 9 represent the isocenter shift vector, thus a combination of the vrt, lng and lat shift. For the evaluation of patient motion, the isocenter shift in the three translational directions was extracted for beam on. For each fraction, a mean isocenter shift in the vrt, lng and lat direction was then calculated for when the radiation had been delivered. To account for both intra- and interfractional movement, the patient's position, registered in cPosition, was added to the isocenter shift values. This resulted in a new isocenter position for every fraction investigated, including both the setup deviations and movements of the patient. In total cMotion data could be extracted for 23 fractions. For the two remaining fractions no isocenter shift was performed, and the original isocenter position was retained in the TPS.

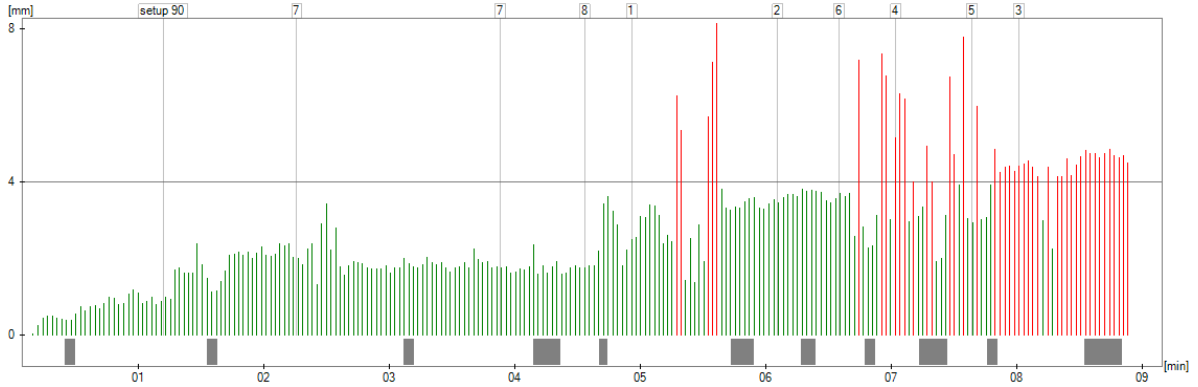
The patient's original treatment plan was copied 25 times in the treatment planning system (TPS) Eclipse™ (Varian Medical Systems, Palo Alto, CA) and for each plan the position of the isocenter was changed according to the calculated mean shifts for each fraction. The treatment plan was then recalculated using the same number of monitor units as the original plan. This means that the radiation would have been delivered with the same settings as the actual delivered dose to the patient, but with a different isocenter position, resulting in a different dose distribution for every fraction. The dose distributions for the 25 isocenter-shifted plans were then summed. This summed dose distribution, with the motion of the isocenter taken into account, was then compared to the original dose distribution by comparing the resulting dose volume histogram (DVH).



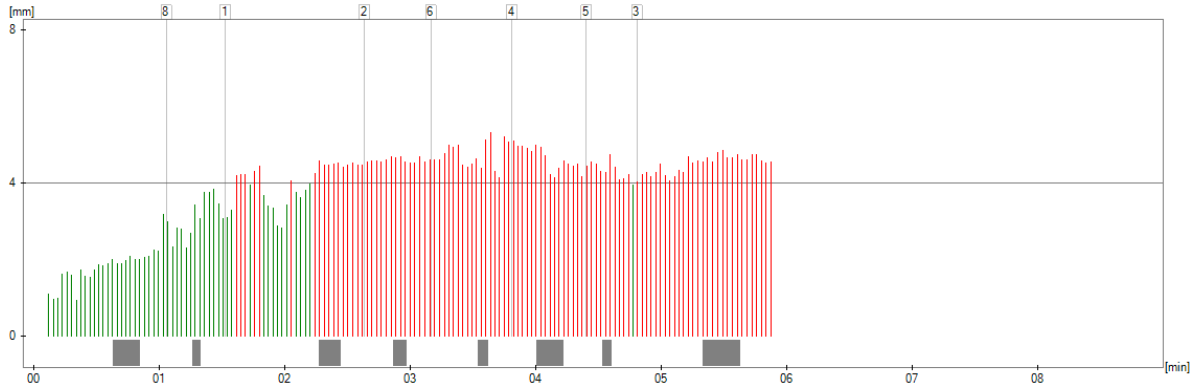
(a)



(b)



(c)



(d)

Figure 9. Example of cMotion data from fraction 18 with low patient movement (a) and fraction 2 (b), fraction 13 (c) and fraction 22 (d) with large patient motion, for the patient whose motion was evaluated.

4. Results

Figure 10 shows histograms displaying the distribution of setup deviations for LBS and SBS, both with and without the offline corrections. For LBS 44 %, 31% and 36% of the setup deviations exceeded the clinical threshold of 4 mm in the vrt, lng and lat direction respectively when the offline corrections were excluded (Figure 10(a)). The range of setup deviation was -10.0–10.4 mm, -11.8–12.7 mm, -8.6–12.2 mm in the vrt, lng and lat direction respectively. By using the correction strategy, the amount of fractions where the patient position exceeded 4 mm was reduced to 22 % in the vrt direction, 21 % in the lng direction and 28 % in the lat direction (Figure 10b). The range of setup deviation was also decreased. With the offline corrections performed included, the range of setup deviations was -10.0–8.7 mm, -11.8–8.6 mm and -8.6–9.2 mm in the vrt, lng and lat direction respectively.

Using SBS, the amount of setup deviations exceeding 4 mm was further reduced. Without the correction strategy 7.5 % of the setup deviations exceed 4 mm in the vrt direction, 7.5 % in the lng direction and 27 % in the lat direction (Figure 10c). The deviations ranged between -5.7–5.4 mm, -5.6–5.1 mm and 7.9–7.0 mm in the vrt, lng and lat direction respectively. By performing offline corrections during the treatment course 7.5 % of the setup deviations exceeded the clinical threshold of 4 mm in the vrt direction. The corresponding values for the lng and lat direction were 6.5 % and 20 % respectively. The deviations ranged from -5.7–5.4 mm in the vrt direction, -5.6–3.7 mm in the lng direction and -7.9–6.0 in the lat direction.

The Shapiro-Wilks test showed that the data representing the distribution of absolute setup deviations for LBS and SBS was not normal in any direction. The Wilcoxon rank sum test was used with the following null hypothesis: *There is no difference in the absolute median between LBS and SBS*. The test was performed with a significance level of 0.05 and this was done for all three directions (Table 3).

Figure 11 shows a comparison between LBS and SBS in the form of cumulative histograms for the absolute value of the setup deviations in the vrt, lng and lat direction. The histograms show the cumulative probability to position the patient within a certain deviation between the planned and daily position. For instance, without the use of a correction strategy there was a 58 % probability of positioning a patient within a deviation of 4 mm in the vrt direction with LBS. For SBS, the corresponding probability was 94 % (Figure 11a).

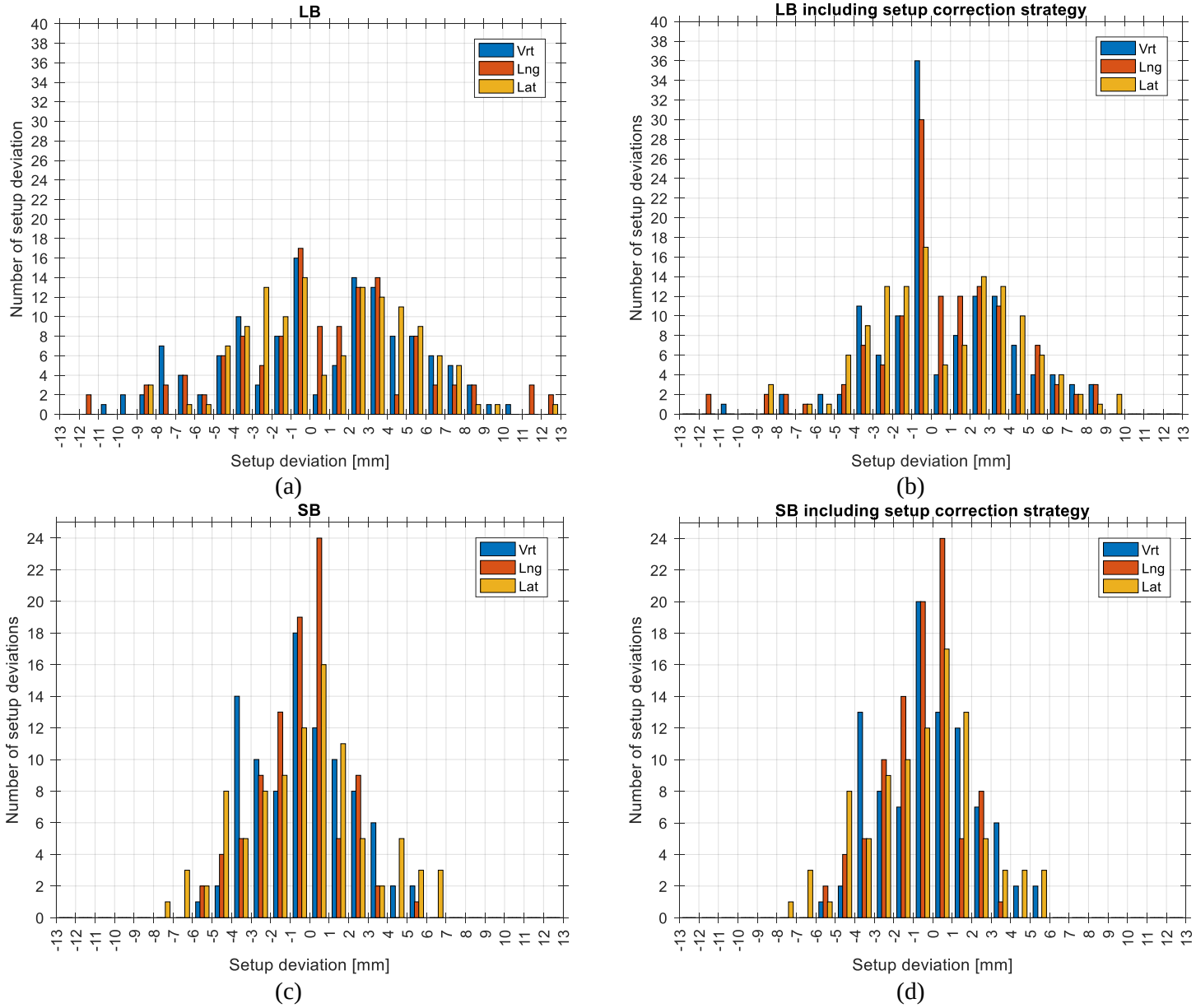


Figure 10. Histograms showing patient setup deviations in the vrt, lng and lat direction for LBS without offline corrections (a), LBS with offline corrections (b), SBS without offline corrections (c) and SBS with offline corrections. and SBS.

Table 3. The absolute median for the setup deviations in vrt, lng and lat for LBS and SBS with the associated *p* – values.

	Vrt – Median (range) [mm]	Lng – Median (range) [mm]	Lat – Median (range) [mm]
LBS	2.7 (0 – 10.0)	2.0 (0 – 11.8)	2.6 (0 – 9.2)
SBS	1.7 (0 – 5.7)	1.0 (0 – 5.6)	1.5 (0 – 7.9)
p	0.067	0.014	0.005

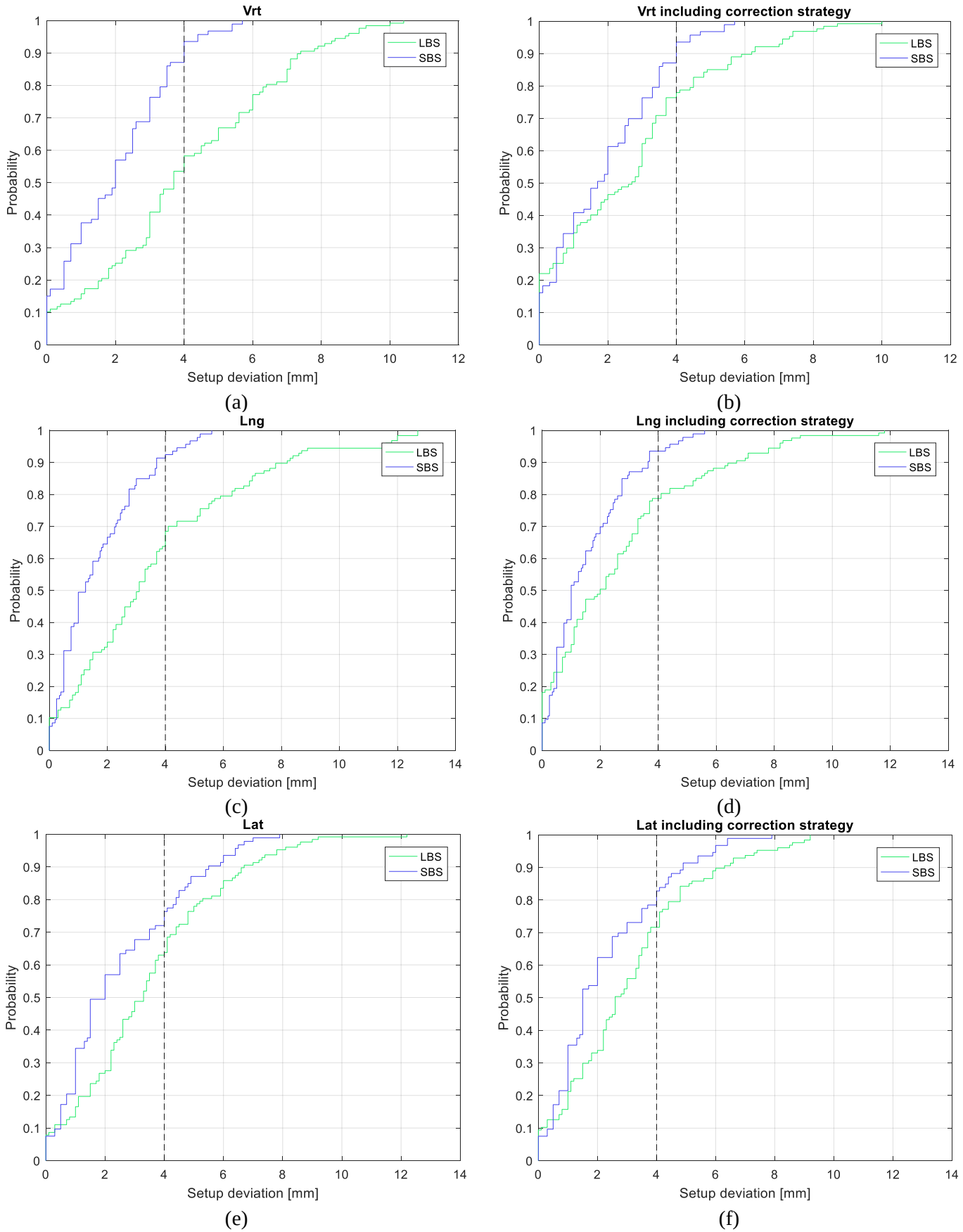


Figure 11. Cumulative histograms for LBS (green) and SBS (blue) in the vrt direction without offline corrections (a), vrt direction with offline corrections (b), lng direction without offline correction (c), lng direction with offline correction (d), lat direction without offline correction (e) and lat direction with offline corrections (f). The dashed vertical lines mark the 4 mm setup deviation threshold.

4.1 Setup Deviations and PTV margins

The resulting overall mean systematic deviation for LBS and SBS is presented in Table 4. The overall mean systematic deviation was calculated for the data without the correction strategy ($m_{o,LBS}$ and $m_{o,SBS}$) and for data including the correction strategy ($m_{o,LBS,c}$ and $m_{o,SBS,c}$). $m_{o,LBS}$ was found to be statistically significant in the lat direction, which indicates that without the correction strategy, there would be a systematic deviation that affects all patients if they are setup with LBS. However, there was no statistical significance for when the correction strategy was applied.

The systematic error for LBS and SBS is shown in Table 5. The systematic error was determined for when the offline corrections were excluded (Σ_{LBS} and Σ_{SBS}) and included ($\Sigma_{LBS,c}$ and $\Sigma_{SBS,c}$). The random setup error for LBS and SBS was also determined for both when the correction strategy was excluded (σ_{LBS} and σ_{SBS}) and included ($\sigma_{LBS,c}$ and $\sigma_{SBS,c}$) (Table 6). Individual systematic and random deviations for each patient for both LBS and SBS are presented in Appendix 1.

Using the determined systematic and random setup errors the PTV margin was determined, both without ($PTV_{m,LBS}$ and $PTV_{m,LBS,c}$) and with offline corrections ($PTV_{m,LBS,c}$ and $PTV_{m,SBS,c}$), see Table 7.

Table 4. The overall mean systematic deviation in the vrt, lng and lat directions for LBS without offline corrections ($m_{o,LBS}$), LBS with offline corrections ($m_{o,LBS,c}$), SBS without offline corrections ($m_{o,SBS}$) and SBS with offline corrections ($m_{o,SBS,c}$). * indicates a value that is statistically significantly non-zero.

	Overall mean systematic deviation			
	$m_{o,LBS}$	$m_{o,LBS,c}$	$m_{o,SBS}$	$m_{o,SBS,c}$
Vrt [mm]	0.72	0.85	-0.07	0.05
Lng [mm]	0.75	0.57	-0.42	-0.59
Lat [mm]	1.2*	0.78	-0.11	-0.32

Table 5. The systematic setup error in the vrt, lng and lat directions for LBS without offline corrections (Σ_{LBS}), LBS with offline corrections ($\Sigma_{LBS,c}$), SBS without offline correction (Σ_{SBS}) and SBS with offline corrections ($\Sigma_{SBS,c}$).

	Systematic error			
	Σ_{LBS}	$\Sigma_{LBS,c}$	Σ_{SBS}	$\Sigma_{SBS,c}$
Vrt [mm]	2.4	1.7	1.7	1.7
Lng [mm]	2.1	2.4	1.3	1.4
Lat [mm]	1.6	2.9	2.6	2.1

Table 6. The random setup error in the vrt, lng and lat directions for LBS without offline corrections (σ_{LBS}), LBS with offline corrections ($\sigma_{LBS,c}$), SBS without offline correction (σ_{SBS}) and SBS with offline corrections ($\sigma_{SBS,c}$).

	Random error			
	σ_{LBS}	$\sigma_{LBS,c}$	σ_{SBS}	$\sigma_{SBS,c}$
Vrt [mm]	4.3	3.1	1.9	1.9
Lng [mm]	4.5	2.9	1.8	1.5
Lat [mm]	3.9	3.4	2.1	2.1

Table 7. The PTV margin in the vrt, lng and lat direction for LBS without offline corrections ($PTV_{m,LBS}$), LBS with offline corrections ($PTV_{m,LBS,c}$), SBS without offline corrections ($PTV_{m,SBS}$) and SBS with offline corrections ($PTV_{m,SBS,c}$).

	$\boldsymbol{PTV_{m,LBS}}$	$\boldsymbol{PTV_{m,LBS,c}}$	$\boldsymbol{PTV_{m,SBS}}$	$\boldsymbol{PTV_{m,SBS,c}}$
Vrt [mm]	9.0	6.0	6.0	6.0
Lng [mm]	9.0	8.0	5.0	5.0
Lat [mm]	7.0	7.0	8.0	7.0

4.2 Dosimetric Effect of Inter- and intrafractional Motion

In Figure 12 the DVH of the original treatment plan and the treatment plan based on the mean isocenter shift for each fraction is shown. At SUS the highest priority for the treatment plan for breast cancer patients with nodal involvement is $D_{98\%} \geq 93$ % for thePTV and 93 % of 50 Gy is 46.5 Gy. $D_{98\%}$ for the original plan was 46.6 Gy. $D_{98\%}$ for the plan where the isocenter has been shifted for each fraction to a calculated mean position was 46.5 Gy. In Table 8 and Table 9 $D_{98\%}$ to the PTV, $D_{2\%}$ to the OAR and the mean absorbed doses are presented for both treatment plans.

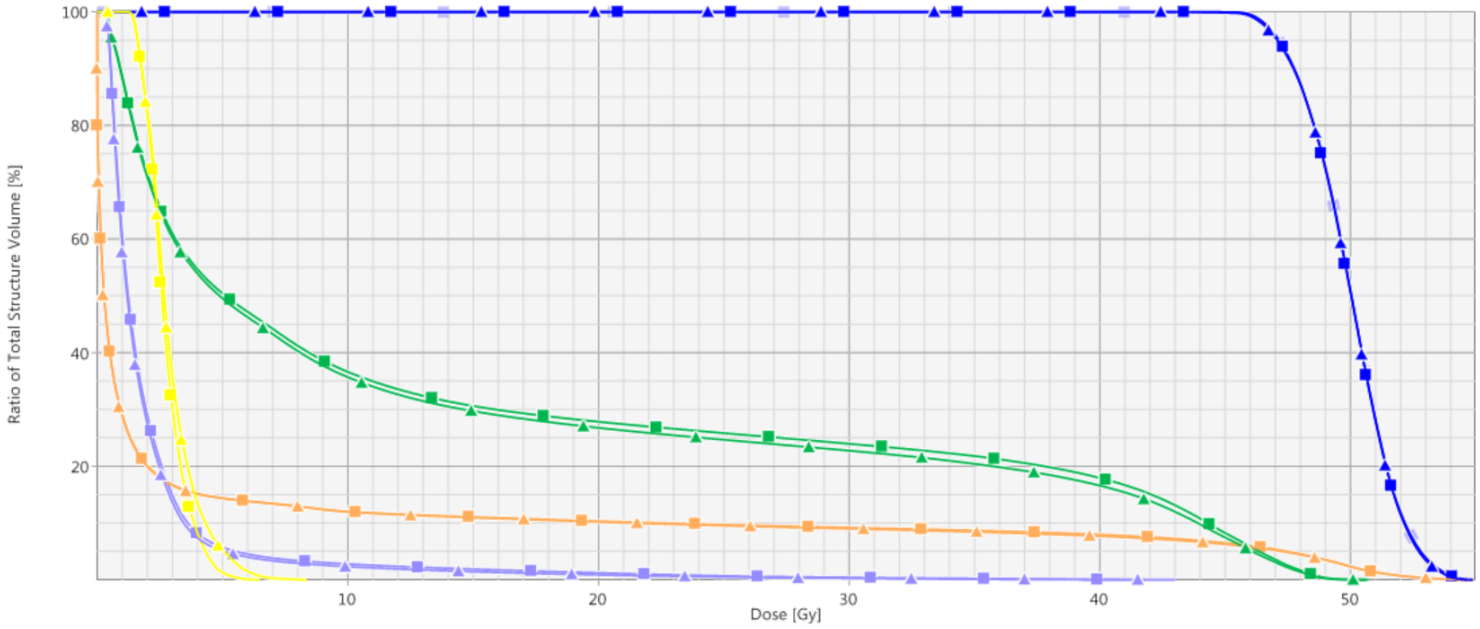


Figure 12. The DVH of the original treatment plan (squares) and the treatment plan resulting from a mean isocenter shift (triangles) for the PTV (blue), left ung (green), heart (purple) spinal cord (yellow) and total body volume (orange).

Table 8. The $D_{98\%}$ and the mean absorbed dose to the PTV.

	$D_{98\%}$ [Gy]		**Mean Dose [Gy]**	
Structure	*Original*	*Mean Iso shift*	*Original*	*Mean Iso shift*
PTV	46.6	46.5	50.0	50.0

Table 9. The $D_{2\%}$ and the mean absorbed dose to the OAR.

	$D_{2\%}$ [Gy]		**Mean Dose [Gy**	
Structure	*Original*	*Mean Iso shift*	*Original*	*Mean Iso shift*
Left lung	47.8	47.6	14.4	13.9
Heart	14.1	11.5	2.16	2.00
Spinal cord	4.77	5.79	2.72	2.90
Body	50.3	50.3	5.42	5.32

5. Discussion

The optical surface scanning system Catalyst have in previous work been proven to be an accurate method for patient positioning [6], [7], [12]. The studies by Kügele *et al.* [6] and Crop *et al.* [7] also showed that patient positioning with the Catalyst is superior to the patient setup with laser and skin markings. In consistency with the mentioned studies, the results presented in this master thesis indicate that the Catalyst is a better method of positioning breast cancer patients with nodal involvement, compared to laser and skin markings.

When studying Figure 10a it can be seen that positioning with laser and skin markings resulted in a large amount of fractions exceeding the clinical setup deviation threshold of 4 mm. Without offline corrections, nearly half of the fractions would exceed 4 mm in the vrt direction. When the correction strategy was included, the setup deviations were smaller and the number of fractions exceeding 4 mm was reduced (Figure 10b). For instance, the number of fractions where a patient was positioned outside the 4 mm threshold was reduced to halved in the vrt direction when the offline corrections were included. This indicate that the correction strategy is useful and beneficial for breast cancer patients with nodal involvement using LBS. However, even with a correction strategy, there were still a considerable amount of fractions with deviations larger than the threshold. For example, in the lateral direction, 28 % of the fractions exceeded the clinical deviation threshold. This implies that for LBS, the patient is not positioned correct in the lat direction for almost a third of all treatment sessions without setup imaging. The results further indicate that positioning exceeding the threshold for what is clinically acceptable in the vrt and lng directions occurs approximately 20 % of all fractions without setup imaging.

The results presented in Figure 10c and d show a distinct improvement in patient positioning for SBS compared to LBS and the amount of setup deviations exceeding 4 mm was reduced in all directions for SBS. This reduction explains why the histograms in Figure 10c and d do not have as long tails as the histograms in Figure 10a and b.

In the vrt and lat direction, 7.5 % of the setup deviations exceeded 4 mm. These results indicate that, on average, patient positioning with more than 4 mm setup deviation vertically or longitudinally from the planned position occurred only two times during the whole treatment course for one patient. This ensures that the Catalyst could be used as a tool for patient setup during fractions when imaging is not performed. However, the amount of setup deviations exceeding 4 mm was not decreased as much in the lateral direction, which indicates that this was the direction the staff thought was most difficult to position correctly with the Catalyst. The position of the arm affects the value of the lateral isocenter shift relatively much. It is possible that the treatment staff did not position the arm correctly at every fraction. This was a new way for the personnel to position this category of patients and the lateral setup of the patient will most likely improve if the personnel continue to position with the Catalyst and gain even more experience of this method. Even so, SBS did reduce the lateral setup deviations and would be the preferred setup method for this direction as well.

As can be seen in Figure 10c and d, there is not a large difference between the histograms with and without offline corrections for SBS. The amount of setup deviations that exceeded 4 mm is slightly higher for the data without offline corrections. This implies that although the correction strategy is beneficial for the patients positioned according SBS, it is not as important as when positioning with LBS.

The results presented in Table 3 confirms that there is a statistical significant difference between LBS and SBS in the lng and lat direction and SBS significantly improve the patient position.

The cumulative histograms of the setup deviations presented in Figure 11, show that the cumulative histogram for LBS is in principle always under that for SBS, regardless of the deviation direction. This implies that the probability for positioning a patient within a given setup deviation was higher for SBS.

The figures also illustrates how the different setup methods were affected by the correction strategy. For LBS, a difference can be seen when comparing the cumulative histograms with and without offline corrections. For instance, the probability of positioning a patient within 4 mm in the vrt direction without oflline corrections was 58 %, as mentioned in section 4. With the use of the correction strategy the corresponding value was 78 %. However, the cumulative histograms representing SBS do not differ to any large extent between excluding and including offline corrections. The probability for positioning a patient within a 4 mm in the vrt direction, using SBS, was 94 % both with and without offline corrections. This further confirms that LBS is more dependent on the correction strategy, while SBS provides a high setup accuracy and is a stable setup method, even without a correction strategy.

5.1 Setup Deviations and PTV margins

The results presented in Table 5 show that the systematic error was decreased when the Catalyst was used for patient setup and the correction strategy was applied. This implies that the mean patient position deviated less from the planned position for SBS and using the Catalyst during setup is the more accurate patient positioning method. For LBS both the lng and lat systematic error was increased when the offline correction were applied. This could be an indication of that the correction strategy used at SUS for decreasing the systematic setup deviations may not be the most optimal strategy for breast cancer patients with nodal involvement.

The random setup error was decreased as well for SBS, for all directions (Table 6). This means that the Catalyst did not only lead to more accurate setup, but a more precise setup as well. While it might not be the most optimal correction strategy, the strategy does seem to improve the setup precision for patients positioned with LBS. The difference between including and excluding offline corrections was however much smaller for SBS.

Further results confirming that the Catalyst offers a more accurate and precise setup method for breast cancer patients with nodal involvement can be seen in Table 10 - Table 13, Appendix 1, where the individual systematic and random deviations are presented. It should be noted that for patient 6 the random deviation without offline correction was almost 1 cm. When the correction strategy was included, both the systematic and random deviation were still larger than 4 mm. This implies that for LBS a patient could be positioned outside of the clinical threshold for setup deviation most of the treatment sessions. Such large deviations were not seen for any patient positioned with SBS.

The PTV margin required to account for both the systematic and random setup error could be reduced in the lng direction for patients positioned with SBS, using the correction strategy (Table 7). This means that the Catalyst requires a smaller PTV than laser and skin markings and more healthy tissue could then be spared.

Some assumption had to be made regarding the offline corrections made for LBS, since no certain documentation of offline corrections was available after the patient had finished the treatment. If there were no other indications, an offline correction was assumed to have been made after the three first fractions and none after this. When information in Offline Review indicated that an offline correction should be done, it was assumed that a correction was performed, regardless of which fraction it concerned. In two cases information in Offline Review, in combination with a new acquired Catalyst surface reference, indicated that offline corrections had been performed. This means that the number of offline corrections actually performed may differ from the number of offline corrections assumed to have been performed. The number of offline corrections actually performed is probably larger than assumed, since all possible, but not definite, corrections after the one done after the first three fractions were disregarded. The setup deviations without offline corrections could therefore actually be larger than presented here. Since all papers with notations on performed offline corrections were saved for the patients positioned according to the Catalyst, there is here no uncertainty of when offline corrections were performed.

Another uncertainty in the data is the inter-observer variability of matching the reference and daily verification images. Different persons might match the images against different anatomical landmarks which give differences in the setup deviation results. If the image quality differs from what the observer is used to, it can also affect the result. In this study only deviations from image matching performed by the treatment room staff, were used. Image matching is also performed by a physicist after treatment, but including the physicist's match would have increased the inter-observer variability. There is a limited number of persons working in the treatment rooms, but the physicist who does the image matching varies from day to day. The setup deviations that resulted from the treatment staffs' image matching also represented the position in which the patient had been given the treatment.

5.2 Dosimetric Effect of Inter- and Intrafractional Motion

The dosimetric result from calculating a mean position for the isocenter during beam on did not differ to any large extent from the original treatment plan. The PTV coverage still met the clinical requirement and the mean absorbed dose to the heart and left lung was slightly lower than in the original plan. This means that despite the large patient motion during treatment, she still received a dose distribution close to the planned one, which is reassuring. The absorbed dose to the spinal cord was slightly increased, but the clinical impact of this increase is probably small.

The treatment room personnel for the investigated patient are all very experienced and skilled in positioning breast cancer patients with nodal involvement according to the Catalyst. Even though the patient moved a lot during some treatment sessions, the accurate patient positioning may have been a contributing factor to the small difference between the original treatment plan and the re-calculated one. Investigating a patient without distinctive movement during treatment, but with an inferior setup might show a different result.

It may also be that this patient moved in a way, for instance by relaxing more during the treatment session, that prevented the heart and lung from receiving a higher absorbed dose.

Perhaps analysing the mean isocenter shift during beam on is not the most representative method for determining how the dose distribution is affected by patient motion. It might be more accurate to extract the isocenter shift for every, individual field instead. As can be seen in Figure 9 the patient tended to drift from the initial position and the isocenter shift was larger during the last fields. The result from analysing each field individually might result in a different absorbed dose to the OAR most affected by the later radiation fields.

As can be seen in Figure 9 the patient has been irradiated although the isocenter vector shift exceeded 4 mm. At SUS, no automatic beam interruption for free breathing breast cancer patients with nodal involvement has been installed. The Catalyst system is, at the moment, used only as a tool to aid the treatment personnel during the patient positioning and monitoring of the patient. The Catalyst is not included in our method for this patient category and it is therefore not a requirement to use the Catalyst during patient positioning and the beam does not have to be interrupted if the patient moves to a large extent during the treatment. Before including positioning and monitoring the patient with the Catalyst, the method has to be evaluated. The results in this thesis indicate that the patient positioning would be improved using the Catalyst. However, the impact of patient motion during treatment has to be further investigated in order to determine an appropriate threshold for the isocenter vector shift. According to this evaluation, the patient investigated did receive a dose distribution close to the planned one. However, any conclusions about how patient movement during the treatment affects the dose distribution cannot be drawn from information from only one patient, and therefore more patients need to be evaluated.

6. Conclusion

Positioning breast cancer patients with nodal involvement using SBS resulted in fewer setup deviations exceeding the clinical acute action level of 4 mm, compared to LBS. Using SBS also led to a smaller systematic error, which means that the mean patient position was improved. The random error was decreased as well and the risk of large, random setup deviations was thereby decreased.

According to this study, using a correction strategy for breast cancer patients with nodal involvement is important for patients positioned with LBS. However, a similar difference between using and not using a correction strategy could not be seen for SBS. This indicates that the Catalyst provides a reliable method for patient positioning.

These results indicate that the Catalyst can improve the patient positioning and provide higher accuracy and precision during setup compared to setup with laser and skin markings. They also reassure that the patient can be positioned correctly even during the fractions where no verification images are acquired.

The evaluation of the dosimetric effect of inter- and intrafractional motion, for one of the patients in this study, indicated only a small impact on the PTV coverage and OAR doses. The differences in the dose distributions were not clinically relevant. However, to be able to draw any definite conclusions about the dosimetric effect due to patient motion more patients have to be evaluated.

7. Future prospects

The purpose of this master thesis was to evaluate if patient positioning was improved using the optical surface scanning system Catalyst. The study showed that positioning leads to smaller systematic and random errors and more patients are positioned within the clinical tolerance for deviation. However, in the future it would be interesting to acquire more data and involve a greater number of patients to improve the statistics of this study.

As mentioned in section 5.2 it would be possible to extract the mean isocenter position for every individual field during each treatment session, instead of assuming the same mean isocenter shift for all fields. Evaluating every field separately would represent the motion of the patient better and would give better estimate of how the PTV coverage and OAR doses are affected by the motion.

To be able to draw any conclusions about how patient motion during treatment affect the dose distribution more patients will have to be evaluated. It would also be interesting to investigate patients who have been setup with LBS, but have also been motion monitored with cMotion. This would provide the possibility to investigate if the improved patient positioning observed with SBS also results in a dosimetric benefit.

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Appendix 1

In Table 10 and Table 11 the individual systematic deviation is presented for LBS and SBS respectively. The systematic deviation in the vrt, lng and lat direction is presented for both the correction strategy excluded and included.

The individual random setup error is presented in Table 12 and Table 13 for LB and SB respectively. The random deviations, both with and without offline corrections in the vrt, lng and lat direction is shown.

Table 10. The individual systematic deviation for patients positioned with LBS, for both without ($m_{p,LBS}$) and with ($m_{p,LBS,c}$) offline corrections.

	Vrt [mm]		**Lng [mm]**		**Lat [mm]**	
Patient	$m_{p,LBS}$	$m_{p,LBS,c}$	$m_{p,LBS}$	$m_{p,LBS,c}$	$m_{p,LBS}$	$m_{p,LBS,c}$
1	0.58	0.58	-0.92	2.8	-2.5	-2.5
2	4.1	1.5	2.3	2.3	1.5	1.5
3	-1.2	0.85	-0.28	-2.3	3.2	3.6
4	-0.23	-2.7	1.6	1.6	1.1	1.1
5	-2.6	1.7	2.6	2.6	2.3	2.3
6	3.1	3.1	4.1	-4.3	-0.31	-0.31
7	1.1	1.1	0.64	0.64	-0.14	-0.14
8	-0.94	-0.94	-2.4	0.70	0.72	0.72
9	1.4	-1.9	-0.92	1.7	1.2	-2.8
10	0.05	2.4	-1.7	-1.7	2.8	1.2

Table 11. The individual systematic deviation for patients positioned with SBS. Values for both without ($m_{p,SBS}$) and with ($m_{p,SBS,c}$) a correction strategy is shown.

	Vrt [mm]		**Lng [mm]**		**Lat [mm]**	
Patient	$m_{p,SBS}$	$m_{p,SBS,c}$	$m_{p,SBS}$	$m_{p,SBS,c}$	$m_{p,SBS}$	$m_{p,SBS,c}$
11	-0.50	-0.50	0.86	0.86	0.43	0.43
12	1.1	1.1	-2.9	-2.9	4.8	2.6
13	-2.6	-0.64	-1.2	-1.2	-3.5	-3.1
14	0.31	0.31	-0.16	-2.4	0.19	0.19
15	-2.1	-2.1	-0.04	-0.04	1.3	1.3
16	1.1	1.1	-1.8	-1.8	-2.1	-2.1
17	-2.4	-3.2	0.08	0.08	-1.1	-1.1
18	1.7	1.7	1.5	1.5	-2.1	-2.1
19	1.3	1.3	-0.3	-0.3	-2.4	-2.4
20	2.1	2.1	0.12	0.12	0.89	0.89
21	-0.81	-0.81	0.21	0.21	2.7	2.7

Table 12. The individual random deviation for patients setup with LBS, for both without ($\sigma_{p,LBS}$) and with ($\sigma_{p,LBS,c}$) offline corrections.

	Vrt [mm]		**Lng [mm]**		**Lat [mm]**	
Patient	$\sigma_{p,LBS}$	$\sigma_{p,LBS,c}$	$\sigma_{p,LBS}$	$\sigma_{p,LBS,c}$	$\sigma_{p,LBS}$	$\sigma_{p,LBS,c}$
1	2.2	2.2	5.2	2.9	1.3	1.3
2	3.9	3.2	2.7	2.7	3.2	3.2
3	5.1	3.4	4.0	2.6	2.9	2.0
4	4.7	3.3	1.5	1.5	1.9	1.9
5	6.8	4.2	2.3	2.3	4.0	4.0
6	2.7	2.7	9.7	4.7	2.9	2.9
7	2.4	2.4	2.7	2.7	3.4	3.4
8	3.1	3.1	4.9	3.3	4.5	4.5
9	5.3	3.2	4.7	2.8	6.7	3.8
10	3.0	2.2	2.8	2.8	5.4	4.1

Table 13. The individual random setup deviation for without ($\sigma_{p,SBS}$) and with ($\sigma_{p,SBS,c}$) the correction strategy in the vertical, longitudinal and lateral direction for patient positioned with SBS.

	Vrt [mm]		**Lng [mm]**		**Lat [mm]**	
Patient	$\sigma_{p,SBS}$	$\sigma_{p,SBS,c}$	$\sigma_{p,SBS}$	$\sigma_{p,SBS,c}$	$\sigma_{p,SBS}$	$\sigma_{p,SBS,c}$
11	1.5	1.5	1.2	1.2	1.8	1.8
12	2.9	2.9	1.6	1.6	1.7	2.3
13	0.77	2.0	1.5	1.5	2.2	2.2
14	1.1	1.1	4.7	2.7	0.64	0.64
15	1.6	1.6	0.83	0.83	2.2	2.2
16	1.0	1.0	1.2	1.2	1.8	1.8
17	2.4	1.3	0.83	0.83	1.9	1.9
18	1.9	1.9	0.86	0.86	3.0	3.0
19	2.0	2.0	1.4	1.4	2.7	2.7
20	2.0	2.0	1.8	1.8	1.2	1.2
21	2.3	2.3	2.2	2.2	2.0	2.0