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Original Research Article

Geometrical analysis for motion monitoring of rigid bodies with optical surface scanning in radiation oncology

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ABSTRACT

Background and purpose: Surface guided radiotherapy can be used to improve patient setup and for accurate intra-fraction motion monitoring in correspondence to the isocenter. For a clinical relevant motion analysis the actual displacement of the entire clinical target volume (CTV) is necessary. Therefore, the aim of this study was to develop a novel assessment method for intra-fraction motion for rigid body structures based on motion data and a geometrical analysis.

Materials and methods: A threshold value on the volume coverage (VC(t)) of the CTV by the planning target volume (PTV) was proposed as online motion monitoring method. Moreover, offline analysis was performed by using heat maps and by calculating VCx, the volume coverage for at least x% of treatment time. The method was applied retrospectively to patient treatment data for whole brain radiation treatment without a thermoplastic mask.

Results: In 132 out of 142 fractions in total the proportion of the CTV that was inside the PTV for at least 99% of the time (VC99) was more than 95%, for a CTV-to-PTV margin of 5 mm. The source-voxel heat map showed which part of the CTV had a reduced coverage and the target heat map showed the movement of the CTV.

Conclusion: Instead of using an action threshold on the movements of the isocenter, a threshold on the VC(t) of the CTV by the PTV was proposed. The heat maps and resulting values of VCx can be used to adapt the VC(t) threshold or the CTV-to-PTV margin for subsequent fractions.

1. Introduction

Accurate patient setup is important in radiotherapy and is commonly achieved by online imaging [1,2]. After the imaging procedure, the setup is improved as much as possible by performing an online shift and/or rotation of the couch. However, posture differences still may occur. This remaining error can be seen as deformations, and cannot be solved by moving the couch only [3–5]. Surface guided radiotherapy (SGRT) can help to improve the initial setup of the patient by correcting posture differences prior to online imaging. SGRT has proven to be of added value for accurate patient setup and is used for different treatment sites [6–11]. After patient setup using SGRT, online imaging needs to be performed for many target volumes, since surface scanning remains a surrogate for the internal target position, and changes in the internal anatomy remain undetected with surface scanning.

In addition to precise patient setup, target volume intra-fraction motion should be minimized as much as possible to ensure accurate dose delivery. Similar to patient setup errors, intra-fraction motion consists of variations in patient position, changes in patient posture, and changes in the internal anatomy. Examples of these various sources of intra-fraction motion are: patient movement on the couch, different orientations of the neck, shoulders or breast, and variations due to movement of internal organs, such as bladder and rectal filling, bowel movement or breathing motion. Optical surface scanning is used to monitor intra-fraction movements of the patient, for a range of clinical sites such as breast, abdomen, and intra-cranial tumors [10–15]. These studies mention the use of a threshold value for the movements of the patient. If the movements exceed this predefined threshold, irradiation can be stopped. However, SGRT was primarily used to monitor intra-fraction motions and a value of the threshold was not motivated.

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Moreover, the thresholds only apply to the isocenter translation and rotation. In addition, the reproducibility and stability of breath-hold can be monitored with SGRT [16,17]. The advantage of using surface scanning is that there is no need for external markers such as tattoos. Moreover, for some applications with a strong relation between target volume and patient surface no additional imaging is needed to position the patient. Other methods of surveillance of patient motion are based on ultrasound and electromagnetic principles. The disadvantage of those localization methods is the need to place internal or external markers [18,11].

Optical surface scanners are based on the projection of light patterns onto the patient's surface, that are captured by cameras, to generate a 3D reconstruction of a surface. The reconstruction of the external surface of an object will be compared to a reference surface, which is in general based on the treatment planning CT-scan. The actual position of the patient is compared to this reference and the translation of and rotation around the isocenter is calculated. A region of interest is set on the surface close to the treatment volume to define where registration is performed. This results in a set of new couch coordinates where the patient position best matches with the reference surface. A threshold on the maximum remaining translation and rotation error is used, to guarantee accurate radiation delivery. However, it is not straightforward to set a threshold on the translations and rotations around the isocenter, because a rotation around the isocenter results in displacements of other points in the volume. Positions with a larger distance from the point of rotation, have a larger displacement as a result of rotation. Consequently, a threshold value on just the isocenter might not be sufficient to guarantee sufficient coverage of the CTV by the PTV due to intra-fraction motion.

The question therefore arises whether the method of reporting the translation and rotation around the isocenter, in combination with an action threshold, is the best way for intra-fraction motion management. For a clinically more relevant intra-fraction movement analysis the actual displacement of all points in a volume has to be determined. Therefore, the aim of this study was to develop a novel assessment method to assess the effect of intra-fraction motion on CTV coverage by the PTV for rigid body structures based on motion data and a geometrical analysis. The proposed method is limited to monitor rigid body movements, such as the brain. The method was applied to a group of whole brain radiation treatment (WBRT) patients, previously irradiated without a thermoplastic mask and using optical surface scanning to illustrate the clinical use of the method [19].

2. Materials and methods

The percentage of the clinical target volume (CTV) that is located inside the planning target volume (PTV), referred to as the volume coverage (VC(t)), was proposed as the new measure for motion monitoring of the CTV. As such, the VC(t) is a function of time.

In addition to the VC(t), so called heat maps were used to gain insight into the movements of the CTV. Two types of heat maps were differentiated: a source-voxel heat map and a target-voxel heat map, superimposed over the CT scan. The source-voxel heat map shows for each voxel of the CTV the percentage of the time that voxel was located in the PTV. The target-voxel heat map presents the proportion of time a voxel of the original CTV was mapped to the voxel in consideration, based on the motion data. In this way, the target-voxel heat map visualizes the movement of the CTV. The VC(t) is a single value indicating whether the CTV is sufficiently covered by the PTV at a point in time, while the heat maps are an addition to this by showing which part of the CTV was not covered by the PTV, and where this part of the CTV moved to, supporting the clinical interpretation. It is not correct to average VC(t) over time, since the spatial distribution of voxels varies over time. To take this spatial variation into account, the proportion of the CTV that was within the PTV for a x percentage of the time, was calculated: VCx. As an example of this offline analysis, VC99, thus the percentage of the voxels of the CTV that was covered by the PTV for at least 99% of the time was calculated. Moreover, VC95 was calculated.

The proposed method was applied to the motion data of WBRT patients of a previous SGRT feasibility study [19]. The study was approved by the medical ethics committee METC Brabant (CCMO register NL61854.028.17), and informed consent was given by the participants. The head of the patients in this study was stabilized in a cushion without using a thermoplastic mask. SGRT was used for setup and online imaging was performed to improve the setup by a couch shift. The CTV consisted of the whole brain and a CTV-to-PTV margin of 5 mm was applied. The radiation treatment consisted of five fractions of 4 Gy with a palliative intention. In total, 30 patients participated in the study and 142 fractions were analyzed. During the treatment, motion of the head was continuously monitored by an optical surface scanning system (Catalyst™, C-RAD AB, Sweden), consisting of a single-camera. A nonrigid version of the iterated closest point registration algorithm was used to calculate translations of the isocenter in lateral, longitudinal, and vertical direction, and pitch, roll, and yaw around the isocenter. Hoisak et al. reported about the technical specifications of the system and the reproducibility is 0.2 mm and it has a motion detection accuracy within 1 mm [11]. The motion monitoring started after online setup correction of the patient. A threshold of 3 mm translation of the isocenter and 3 degrees rotation around the isocenter was set during monitoring. A value of the isocenter above the threshold meant that a patient needed to be re-positioned. If this happened, irradiation was stopped, and if the position of the patient did not return within threshold values the technologists repositioned the patient on the couch.

In the present study, the CT images, DICOM structure sets, and motion data were analyzed using MATLAB R2015b (The MathWorks, Inc., Natick, USA). To increase the accuracy of the algorithm, the volumes were mapped in a coordinate system with voxels of 0.5x0.5x0.5 mm instead of the original CT grid (0.94x0.94x2.5) using a nearest-neighbor interpolation. A tool was created to apply the intra-fraction motion of the isocenter measured by the surface scanner to the CTV. Subsequently, the VC was calculated as a function of time to simulate a treatment with a threshold on the VC(t). CTV-to-PTV margins of 5 mm, 3 mm, and 1 mm were simulated. Moreover, source-voxel and target-voxel heat maps were calculated. To quantify the information in the source-voxel heat map, VC99 and VC95 were calculated for all fractions for a CTV-to-PTV margin of 5 mm and 3 mm. The analysis method in Matlab was verified by calculating the VC(t) of a cube of different size and shape, by translating and rotating it by known values.

3. Results

An example of the usage of a threshold value for the VC(t) over the course of one treatment fraction is given in Fig. 1. During the measurement, the translation magnitude and roll increased. The VC(t) decreased slightly below 100% when a CTV-to-PTV margin of 5 mm was applied, while the translation and roll increased. When a CTV-to-PTV margin of 3 mm was applied the VC(t) decreased more and for a CTV-to-PTV margin of 1 mm the VC(t) dropped below 99%.

3.1. Source-voxel and target-voxel heat map

The heat maps were used to reflect on the movements of the CTV during a measurement. Fig. 2 is an example of a source-voxel heat map. The sagittal slice indicates a reduced coverage in that part. Considering the CTV volume, 97% or 99% was inside the PTV for at least 99% or 95% of the time respectively. As expected, the corresponding target-voxel heat map in Fig. 3 shows that the CTV moved in caudal direction. The figure shows where CTV voxels moved to. Some voxels moved outside the CTV, but not so far that they were located outside the PTV.

The information in the source-voxel heat map was quantified by calculating the VC99, the proportion of the CTV that was covered by the PTV for at least 99% of the time. Fig. 4 shows VC99 for all five fractions

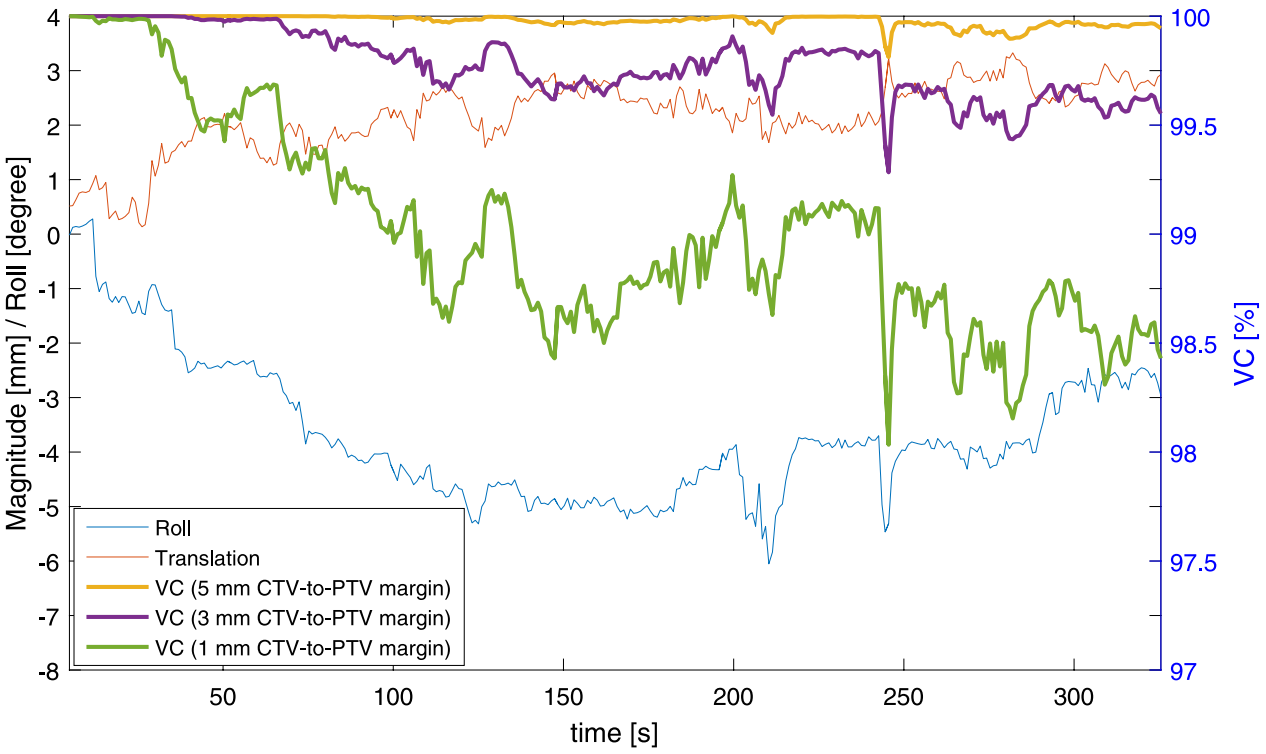

Fig. 1. The translation and roll (left axis) plotted over time, in combination with the VC(t) (right axis) for a CTV-to-PTV margin of 5 mm, 3 mm, and 1 mm (patient #1, fraction 4).

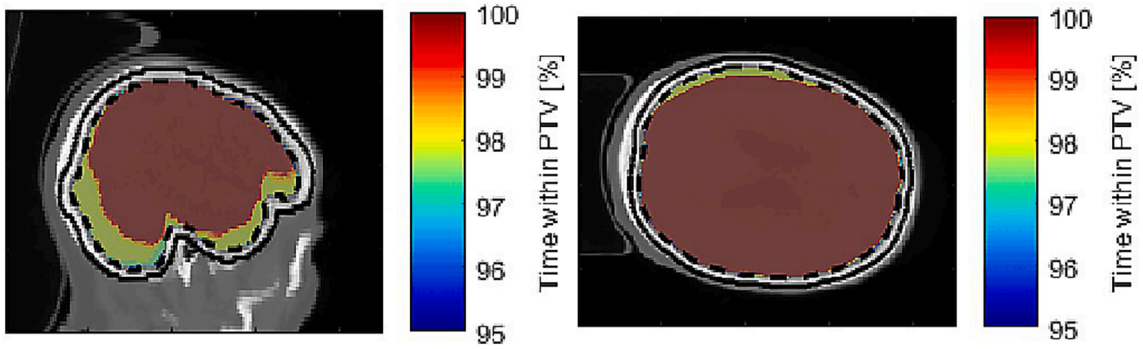

Fig. 2. Source-voxel heat map of patient #2, fraction 5. The colors represent the percentage of the time the voxel of the CTV was in the PTV. The original CTV (dashed line) and the PTV (continuous line) were superimposed on the CT scan for a sagittal (left) and transversal slice (right). Note the different color scales for source-voxel and target-voxel heat map.

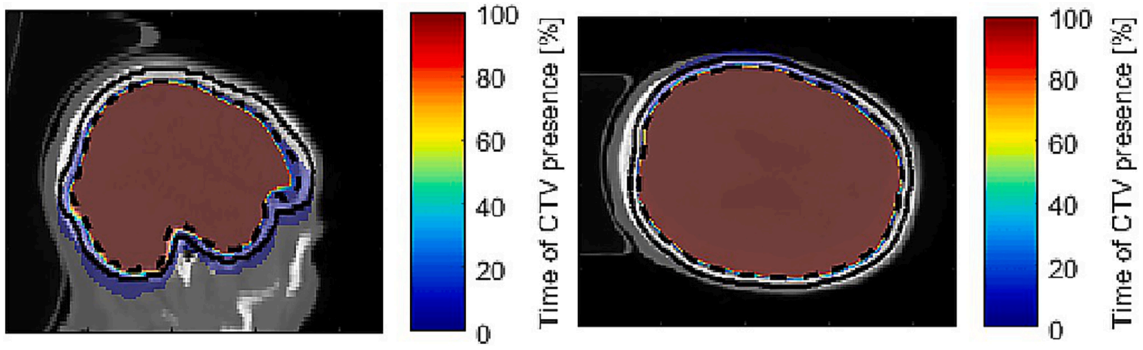

Fig. 3. Target-voxel heat map of patient #2, fraction 5 (same slices as in Fig. 2). The colors represent the percentage of the time a voxel of the CTV was at that location, scaled from 0 (blue) to 1 (red). The original CTV (dashed line) and the PTV (continuous line) were superimposed on the CT scan for a sagittal (left) and transversal slice (right). Note the different color scales for source-voxel and target-voxel heat map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

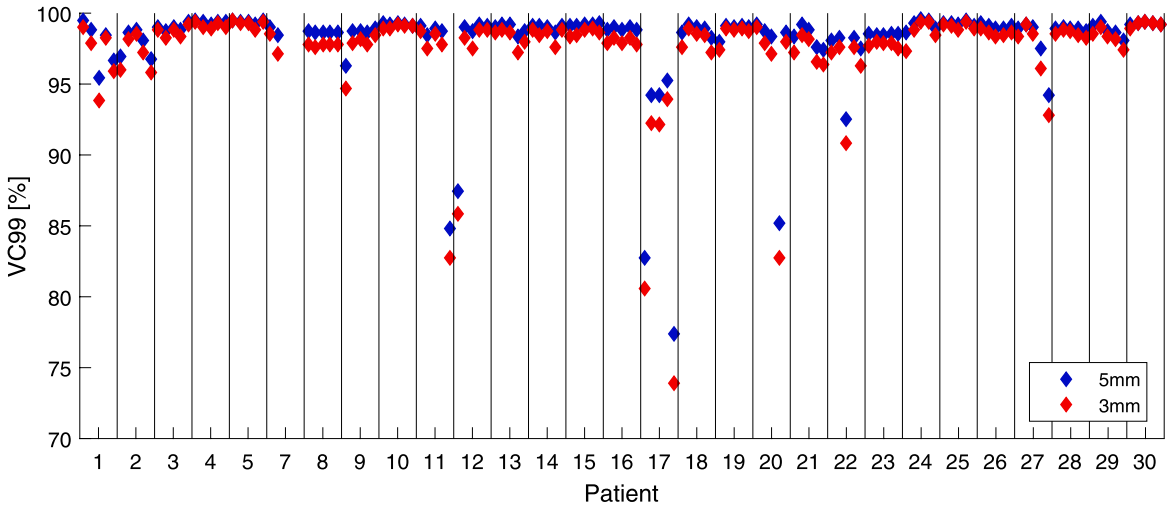

Fig. 4. VC99, the percentage of the CTV voxels that were inside the PTV for at least 99% of the time, for a CTV-to-PTV margin of 5 mm and 3 mm.

for every patient. This ranged from 77% to 100% and from 74% to 100% for a CTV-to-PTV margin of 5 mm and 3 mm, respectively. In 132 out of 142 fractions the VC99 was more than 95% for a CTV-to-PTV margin of 5 mm. Considering VC95, the percentage of the CTV voxels that were inside the PTV for at least 95% of the time, this was more than 95% for all fractions for a CTV-to-PTV margin of 5 mm (Fig. 5). VC95 ranged from 97% to 100% and from 95% to 100% for a CTV-to-PTV margin of 5 mm and 3 mm, respectively.

4. Discussion

An alternative method was developed to assess intra-fraction motion using optical surface scanning. The method presented in this study was applied to WBRT patients of a previous study. The patients were positioned on the treatment couch without using a thermoplastic mask and the intra-fraction movements were monitored.

By using the VC(t) as outcome measure, there is just one value to evaluate that takes into account movements of the whole CTV. This makes the clinical interpretation more clear, compared to the different translations and rotations around the isocenter, where the clinical consequences of, for example, a roll of 3 degrees is not immediately clear, because it is dependent on the size and shape of the CTV. When the VC is used offline to evaluate the intra-fraction motions, it is necessary to take the spatial variation into account. This was visualized by the heat maps. The source-voxel heat map shows parts of the CTV that were not covered by the PTV for the entire fraction. The target-voxel heat map gives insight into motion of the CTV during the fraction and shows the direction the CTV has moved to. This information was quantified by calculating the percentage of the CTV voxels that were inside the PTV for 99% and 95% of the time, VC99 and VC95. A value of 95% for VC99 was achieved in 132 out of 142 fractions in total, for a CTV-to-PTV margin of 5 mm. Assuming it is clinically sufficient to have VC95 $>$ 95%, this was achieved in all fractions of the study. However, VC95 and VC99, and the threshold value on the percentage of the CTV, were arbitrarily chosen. Various aspects, such as the treatment volume, and a palliative or curative intention of the treatment, determine which threshold value is clinically sufficient. At least, this parameter can be used to report on the quality of the treatment with respect to intra-fraction motion.

In a previous study of Dekker et al., using the same 30 WBRT patients, a mean intra-fraction isocenter deviation of 1.1 mm was reported and it was concluded that irradiation without a mask is clinically feasible using a CTV-to-PTV margin of 5 mm [19]. The analysis described in this paper was intended as an example to apply an improved analysis on intra-fraction motion management. The

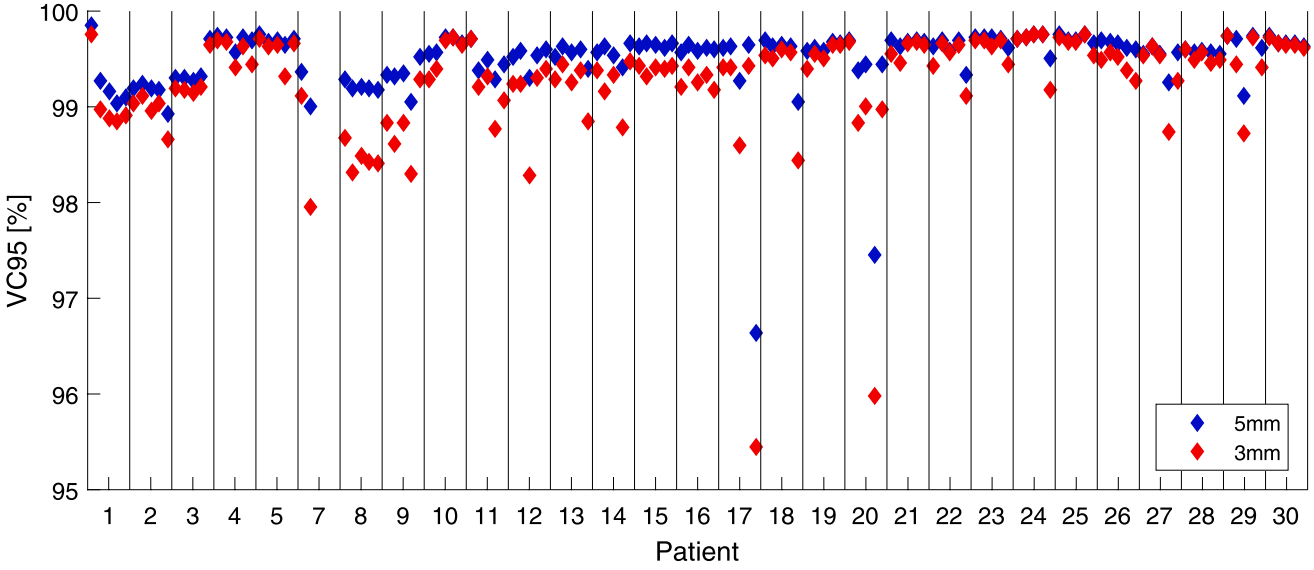

Fig. 5. VC95, the percentage of the CTV voxels that were inside the PTV for at least 95% of the time, for a CTV-to-PTV margin of 5 mm and 3 mm.

conclusion of the former study was further supported by the results in this study.

Various geometrical aspects determine the value of the VC for identical translations and rotations. First, the shape of the CTV is important, and this can be explained as follows. Under rotation, an elongated volume tends to move outside the PTV more at the edges compared to a spherical volume when the isocenter is placed near the center of the object. Second, the absolute volume of the CTV is important because larger volumes have higher volume coverage for similar motions and margins. Translations and rotations have a different effect on the VC. The smaller the object size, the larger the effect that translations have on the VC and the smaller the effect that rotations have. Similar to the example of the elongated shape, points further away from the rotation point, undergo a larger translation as a result of the rotation. A promising clinical application of the proposed method is to use it for treatment plans with a single isocenter and multiple treatment volumes, such as stereotactic neuro surgery of the brain [20]. This is comparable to the example of an elongated shape, where the CTV is located far from the isocenter.

Another overlap-based metric is the Dice coefficient, which is used in validating medical volume segmentation [21]. Similarity exists with the VC. However, the Dice coefficient represents the amount of overlap with respect to the average size of the two volumes, where the VC is related to the original volume only.

In this study, the threshold value was only applied to the VC(t) of the CTV in the PTV. Obviously, other volumes can be taken into account as well. Similar to the motions of the CTV, any movement of the organs at risk (OAR) must be considered. To compensate for set-up uncertainties and intra-fraction movements a margin can be added to the OAR, similar to the PTV, leading to the planning organ at risk volume (PRV) [22]. In analogy with the threshold for the CTV VC(t), a threshold value for the OAR VC(t) can be chosen.

The intra-fraction measurements showed the displacement and rotations of the volume of interest in the isocenter. It depends on the treatment plan how this affects the dose distribution. As long as the CTV stays within the PTV, the dose coverage is sufficient. If the VC(t) becomes less than 100% (i.e. the CTV is outside the PTV), the effect on the dose coverage depends on the treatment technique. The treatment plan for, e.g., WBRT consists of two lateral fields, hence a translation in lateral direction or roll of the head is of minor influence. On the other hand, a longitudinal translation or pitch could have a significant effect on the dose distribution. To calculate the effect of intra-fraction movements on the CTV dose coverage, the method presented in this paper could be extended with integrated dose calculations over time. However, more sophisticated software will be required to perform these calculations.

The applicability of the external surface of a patient as a surrogate for internal intra-fraction movement is limited by the correlation between movements of the surface and the internal anatomy. For a rigid body like the head in WBRT, there is a direct relationship between the surface and the internal anatomy. For other regions, surface deviations can act as a surrogate for superficially located tumors. For deeper located tumors, surface imaging can be complemented by online intra-fraction imaging [10].

Studies described in literature using SGRT addressed intra-fraction motion just as isocenter movements [10–15]. Especially for a large CTV, or a treatment plan with multiple treatment volumes, reporting movements of the isocenter alone is not sufficient. Real-time calculation of the VC(t) of the CTV is necessary to use this method during radiation treatment. With a connection between the linear accelerator and the surface scanner, irradiation can be interrupted automatically if the threshold is exceeded. Further research is required to propose and validate threshold values on the VC(t) for different treatment volumes.

To summarize, a method was described to investigate intra-fraction motions of rigid bodies measured with optical surface scanning during radiation treatment. The VC(t) was proposed as the clinically relevant parameter for intra-fraction motion. The heat maps enable visual evaluation of intra-fraction motions. It gives an indication which CTV-to-PTV margin is appropriate. We proposed to use the heat maps offline to adapt the threshold value or the CTV-to-PTV margin for the next fraction, based on the judgement of the physician and physicist. Moreover, offline values of, for example, VC99 or VC95 can be calculated to provide simple parameters to characterize the quality of the treatments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Gupta T, Narayan CA. Image-guided radiation therapy: Physician’s perspectives. J Med Phys 2012;37:174–82.
[2] Verellen D, Ridder MD, Storme G. A (short) history of image-guided radiotherapy. Radiother Oncol 2008;86:4–13.
[3] Lyatskaya Y, Lu HM, Chin L. Performance and characteristics of an IR localizing system for radiation therapy. J Appl Clin Med Phys 2006;7:18–37.
[4] Verellen D, Ridder MD, Linthout N, Tournel K, Soete G, Storme G. Innovations in image-guided radiotherapy. Nat Rev Cancer 2007;7:949–60.
[5] de Kruijf WJM, Martens RJW. Reducing patient posture variability using the predicted couch position. Med Dosim 2015;40:218–21.
[6] Walter F, Freislederer P, Belka C, Heinz C, Söhn M, Roeder F. Evaluation of daily patient positioning for radiotherapy with a commercial 3D surface-imaging system (Catalyst). Radiat Oncol 2016;11:1–8.
[7] Wikström K, Nilsson K, Isacsson U, Ahnesjö A. A comparison of patient position displacements from body surface laser scanning and cone beam CT bone registrations for radiotherapy of pelvic targets. Acta Oncol 2014;53:268–77.
[8] Hoisak JDP, Pawlicki T. The Role of Optical Surface Imaging Systems in Radiation Therapy. Semin Radiat Oncol 2018;28:185–93.
[9] Moser T, Habl G, Uhl M, Schubert K, Sroka-Perez G, Debus J, et al. Clinical evaluation of a laser surface scanning system in 120 patients for improving daily setup accuracy in fractionated radiation therapy. Int J Radiat Oncol Biol Phys 2013;85:846–53.
[10] Freislederer P, Kügele M, Öllers M, Swinnen A, Sauer TO, Bert C, et al. Recent advances in Surface Guided Radiation Therapy. Radiat Oncol 2020;15:1–11.
[11] Hoisak JDP, Paxton AB, Waghorn B, Pawlicki T. Surface Guided Radiation Therapy. CRC Press; 2020.
[12] Covington EL, Fiveash JB, Wu X, Brezovich I, Willey CD, Riley K, et al. Optical surface guidance for submillimeter monitoring of patient position during frameless stereotactic radiotherapy. J Appl Clin Med Phys 2019;20:91–8.
[13] Hattel SH, Andersen PA, Wahlstedt IH, Damkjær S, Saini A, Thomsen JB. Evaluation of setup and intrafraction motion for surface guided whole-breast cancer radiotherapy. J Appl Clin Med Phys 2019;20:39–44.
[14] Wiant DB, Wentworth S, Maurer JM, Vanderstraeten CL, Terrell JA, Sintay BJ. Surface imaging based analysis of intrafraction motion for breast radiotherapy patients. J Appl Clin Med Phys 2014;15:1–17.
[15] Zhao B, Maquilan G, Jiang S, Schwartz DL. Minimal mask immobilization with optical surface guidance for head and neck radiotherapy. J Appl Clin Med Phys 2018;19:17–24.
[16] Cerviño LI, Gupta S, Rose MA, Yashar C, Jiang SB. Using surface imaging and visual coaching to improve the reproducibility and stability of deep-inspiration breath hold for left-breast-cancer radiotherapy. Phys Med Biol 2009;54:6853–65.
[17] Gierga DP, Turcotte JC, Sharp GC, Sedlacek DE, Cotter CR, Taghian AG. A voluntary breath-hold treatment technique for the left breast with unfavorable

cardiac anatomy using surface imaging. Int J Radiat Oncol Biol Phys 2012;84: e663–8.
[18] D'Ambrosio DJ, Bayouth J, Chetty IJ, Buyyounouski MK, Price RA, Correa CR, et al. Continuous localization technologies for radiotherapy delivery: Report of the American Society for Radiation Oncology Emerging Technology Committee. Pract Radiat Oncol 2012;2:145–50.
[19] Dekker J, Rozema T, Böing-Messing F, Garcia M, Washington D, de Kruijf W. Whole-brain radiation therapy without a thermoplastic mask. Phys Imaging Radiat Oncol 2019;11:27–9.
[20] Swinnen ACC, Öllers MC, Loon Ong C, Verhaegen F. The potential of an optical surface tracking system in non-coplanar single isocenter treatments of multiple brain metastases. J Appl Clin Med Phys 2020:1–20.
[21] Taha AA, Hanbury A. Metrics for evaluating 3D medical image segmentation: analysis, selection, and tool. BMC Med Imag 2015;15.
[22] Berthelsen AK, Dobbs J, Kjellén E, Landberg T, Möller TR, Nilsson P, et al. What's new in target volume definition for radiologists in ICRU Report 71? How can the ICRU volume definitions be integrated in clinical practice? Cancer Imag 2007;7: 104–16.