Physics and Imaging in Radiation Oncology 23 (2022) 134–139

Contents lists available at ScienceDirect

Physics and Imaging in Radiation Oncology

journal homepage: www.sciencedirect.com/journal/physics-and-imaging-in-radiation-oncology

Intrafractional monitoring of patients using four different immobilization mask systems for cranial radiotherapy

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A B S T R A C T

Background and purpose: Patients receiving cranial radiotherapy are immobilized with a thermoplastic mask to restrict patient motion. Depending on the target volume margins and treatment dose, different mask systems are used. Intrafractional movements can be monitored using stereoscopic X-ray imaging. The aim of the present work was to compare the magnitudes of intrafractional deviation for different mask systems.

Material and methods: Four different head mask systems (open face mask, open mask, stereotactic mask, double mask) used in the treatment of 40 patients were investigated. In total 487 treatment fractions and 3708 X-ray images were collected. Deviations were calculated by comparison of the acquired X-ray images with digitally reconstructed radiographs. The results of intrafractional X-ray deviations for translational and rotational axes were compared between the different mask systems.

Results: Deviations were below 0.6 mm for translations and below 0.6° for rotations for all mask systems. Along the lateral and longitudinal directions the stereotactic mask was superior, while along the vertical direction the double mask showed the lowest deviations. For low rotational deviations the double mask is the best amongst all other mask systems.

Conclusion: As expected, the lowest movement was shown using cranial stereotactic mask systems. The results have shown deviations lower than 0.6 mm and 0.6° using any of the four thermoplastic mask systems.

1. Introduction

Immobilization by thermoplastic masks is considered standard of care for cranial irradiation. The masks are fitted to every patient shortly before the acquisition of planning computed tomography (CT) scans, and are subsequenty used to immobilize the patient in a reproducible position throughout the radiation course. Thermoplastic masks usually cover the whole face, which may cause discomfort for certain patients [1]. To increase patient comfort, and especially for patients who are claustrophobic, open masks were introduced. These typically leave the forehead, eyes and nose uncovered. In head and neck cancer radiotherapy open masks have already been investigated and studies showed no significant immobilization difference compared to closed mask systems [2–4].

In cranial stereotactic radiosurgery (SRS), frame-based approaches are uncommon nowadays. Mask-based approaches have a similar precision and are far more comfortable given that they are non-invasive and less painful for patients [5,6].

Commonly, when cranial stereotactic radiosurgery or fractionated stereotactic radiotherapy (FSRT) is applied, a more secure fixation is necessary to hold the head of the patient in the correct position and to ensure that movements are reduced to a minimum. Due to the small gross target volume (GTV) to planned target volume (PTV) margins, which range from zero to only a few millimeters, and the high dose gradients used, even minimal deviations can lead to a geographic miss or overdosage of adjacent organs at risk. Therefore, thermoplastic head masks made of a more rigid material are used [7–9].

Recent developments in surface guided radiotherapy (SGRT) allow monitoring the patient surface in a non-invasive way in real time for initial positioning, as well as for intrafractional monitoring. However, SGRT is only feasible when used with open mask systems [10].

Since the closed mask systems used for SRS or FSRT hinder surface visibility for SGRT-monitoring, and to prevent a bias due to different measurement methods, X-ray images are acquired as reference during the treatment session.

Intrafractional motion in different mask systems using X-ray based imaging techniques (X-ray or cone beam computed tomography [CBCT]) was investigated previously. Badakhshi et al. analyzed intrafractional displacements after each couch rotation using X-rays resulting in mean 3D-vector magnitudes of 1 mm [11]. The stereotactic mask

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https://doi.org/10.1016/j.phro.2022.07.002
Received 30 September 2021; Received in revised form 16 July 2022; Accepted 18 July 2022
Available online 25 July 2022

systems used in the present work have also been studied by Lesiuk et al., Shah et al. and Agazaryan et al. They could all show mean deviations smaller than 0.7 mm [12–14]. Barnes et al. reported deviations of only 0.1 mm along each axis [15]. Similarly, double mask systems used by Tomihara et al. resulted in an average 3D-deviation of 0.2 mm [16]. Lightstone et al. used classic thermoplastic masks for brain irradiation and showed a displacement of about 0.8 mm between pre- and post-treatment CBCT [17]. While closed masks have been extensively studied, to the best of our knowledge there are no studies investigating intrafractional motion with open mask systems using X-ray imaging as reference.

The aim of the present study was to assess intrafractional motion under immobilization by four different mask systems. Furthermore, we aimed at comparing the different systems and at identifying the best solution for cranial irradiation.

2. Material and methods

Between September 2020 and January 2021 patients who received cranial irradiation at the Department of Radiation Oncology, University Hospital, LMU Munich using a Versa HD (Elekta AB, Sweden) linear accelerator (LINAC) and image-guidance with the ExacTrac Dynamic system were consecutively recruited in a prospective study.

The study was approved by the local ethics committee of the University Hospital, LMU Munich (No. 20–664 ex 09/2020) and registered at German Clinical Trials Register (DRKS-ID: DRKS00025304). Written informed consent was obtained from all participants.

2.1. Patient and tumour/treatment characteristics

In our clinic, every patient is offered an IT-V open mask (ITVOM – IT-V [Innovative Technologie Völp e.U., Innsbruck, Austria] iCAST Head Double Micro Open Mask) or a Brainlab open face mask (BLOF – Brainlab [Brainlab AG, Germany] Cranial 4Pi Open Face Mask) for non-SRS (if SGRT is provided) and FSRT (if single doses ≤5 Gy) or an IT-V double mask (ITVDM – IT-V iCAST Head Micro Double) or Brainlab stereotactic mask (BLSRS – Brainlab Cranial 4Pi Stereotactic Mask) for SRS and FSRT (if single doses are >5 Gy). The present study cohort included 40 patients with a median age at diagnosis of 60 years (range: 28–83 years). Of all patients 25% (10/40) were treated for benign diseases (vestibular schwannomas and meningiomas), 25% (10/40) were treated for brain metastasis with single fraction stereotactic radiosurgery, while 22.5% (9/40) were treated for brain metastasis using FSRT (up to 5 fractions), 20% (8/40) received radiotherapy for malignant brain tumours, 5% (2/40) whole brain radiotherapy in case of multiple brain metastasis and 1/40 patient was treated on a pseudotumor of the orbita (see Table 1). Overall, 487 treatment fractions with 3708 stereoscopic images were evaluated (resulting in a mean of 7.6 stereoscopic images per treatment session). Of all acquired stereoscopic X-ray images 61% were in a coplanar treatment setting. The mean number of stereoscopic images that were acquired during a treatment session were 6 (ITVOM), 7 (BLOF), 10 (ITVDM), 19 (BLSRS).

RT related information and patient characteristics were retrieved from medical records. Table 1 gives an overview of the tumor entities and the different mask systems that were used, as well as the number of patients, treatments and acquired stereoscopic X-ray images.

The ExacTrac Dynamic (Brainlab AG, Germany) provides a combination of X-ray imaging and hybrid optical surface (structured light) and thermal imaging scanner. The thermal camera acts as an additional registration information ("4th dimension") which makes multiple in-room cameras unnecessary [10]. However, in this work on intrafractional motion detection only X-ray data were used to analyse intrafractional motion, as especially closed stereotactic mask systems do not expose enough surface for surface scanning. Moreover, X-ray-based image-guidance in SRS and FSRT is based on bone matching, which is a very reliable and standard method for head positioning [18,19].

2.2. Clinical workflow

At the planning computed tomography (CT) scan, an individual thermoplastic mask was fitted to the patient. In Fig. S1 the four different mask systems are shown. For various reasons, not every patient is able to lie flat on the treatment couch. In these cases an additional patient positioning system (headSTEP, IT-V, Innsbruck, Austria) is used as a positioning aid to raise the head position in combination with the IT-V masks (see Fig. S2).

All patients received volumetric arc therapy (VMAT) with the exception of one patient who received a 3D-conformal radiation therapy (3D-CRT) treatment plan. After the initial SGRT assisted positioning with the ExacTrac Dynamic, stereoscopic kV (kilovolt) X-rays images of the skull structures are acquired for sub-millimeter position corrections by comparison with digitally reconstructed radiographs (DRR). Deviations along 6 degrees of freedom (DOF) are obtained (3 translations: lateral, longitudinal, vertical; 3 rotations: roll, pitch, yaw), which are subsequently sent to the robotic Hexapod couch (Elekta HexaPOD evo RT System with iGUIDE 2.2.x, Elekta AB, Sweden). Then, another stereoscopic X-ray image is made to verify the corrected position.

During the irradiation, intrafractional stereoscopic X-ray images were acquired at gantry positions 0°, 90°, 180° and 270°. Based on the registration of these X-ray images to the previously generated DRRs, the system automatically detects deviations along the 3 translations and 3 rotations. In case of a measured deviation larger than 0.5 mm or 0.5° in SRS (or larger than 1 mm or 1° in non-SRS treatments), the treatment beam is held and the patient is automatically re-positioned according to the measured X-ray deviation. Fig. S3 shows a screenshot of the monitored ExacTrac Dynamic data during irradiation.

Table 1
Number of patients, treatment sessions and stereoscopic images as well as entities and kind of treatment per mask[1].

		BLOF	BLSRS	ITVDM	ITVOM	Sum
Patients number		10	9	12	9	40
Treatment sessions		198	25	63	201	487
Stereoscopic images	**Coplanar**	826	393	323	732	2274
	non-coplanar	539	81	300	514	1434
Images per session		7	19	10	6	
Entity/Treatment	**VS&meningeomas**	4	1	1	4	10
	gliomas	3	1	0	4	8
	brain metastasis/WBRT	1	0	0	1	2
	brain metastasis/FSRT	1	1	7	0	9
	brain metastasis/SRS	0	6	4	0	10
	others	1	0	0	0	1

[1] VS: vestibular schwannoma; WBRT: whole brain radiotherapy; FSRT: fractionated stereotactic radiotherapy; FRT: fractionated radiotherapy; SRS: stereotactic radiosurgery.

2.3. Data processing

X-ray-based deviation data in 6 DOF (lateral, longitudinal and vertical translational position deviations in millimeters; roll-, pitch- and yaw-angles for rotational deviations in degrees) were retrieved from PDF-file records which are generated for every treatment session of a patient.

A deviation/magnitude vector was calculated.

$(d = \sqrt{x^2 + y^2 + z^2} = \sqrt{lateral^2 + longitudinal^2 + vertical^2})$ to show the absolute translational deviation.

For patients receiving SRS or FSRT, coplanar (treatment couch 0°) and non-coplanar (treatment couch other than 0°) beam configurations are often used to obtain highly conformal, sharp dose gradients outside the PTV to minimize dose to adjacent tissue or organs at risk [20,21].

The treatment plan complexity correlates with the numbers of X-ray pairs during a treatment session, which can be used as a surrogate for the treatment time. In non-stereotactic treatements with open mask systems one or two arcs in a coplanar setting are typically irradiated per treatment session. Usually three intrafractional X-ray pairs per arc are acquired (resulting in 3–6 X-ray pairs). Stereotactic treatments (where the closed mask systems are used) have more non-coplanar angles and also

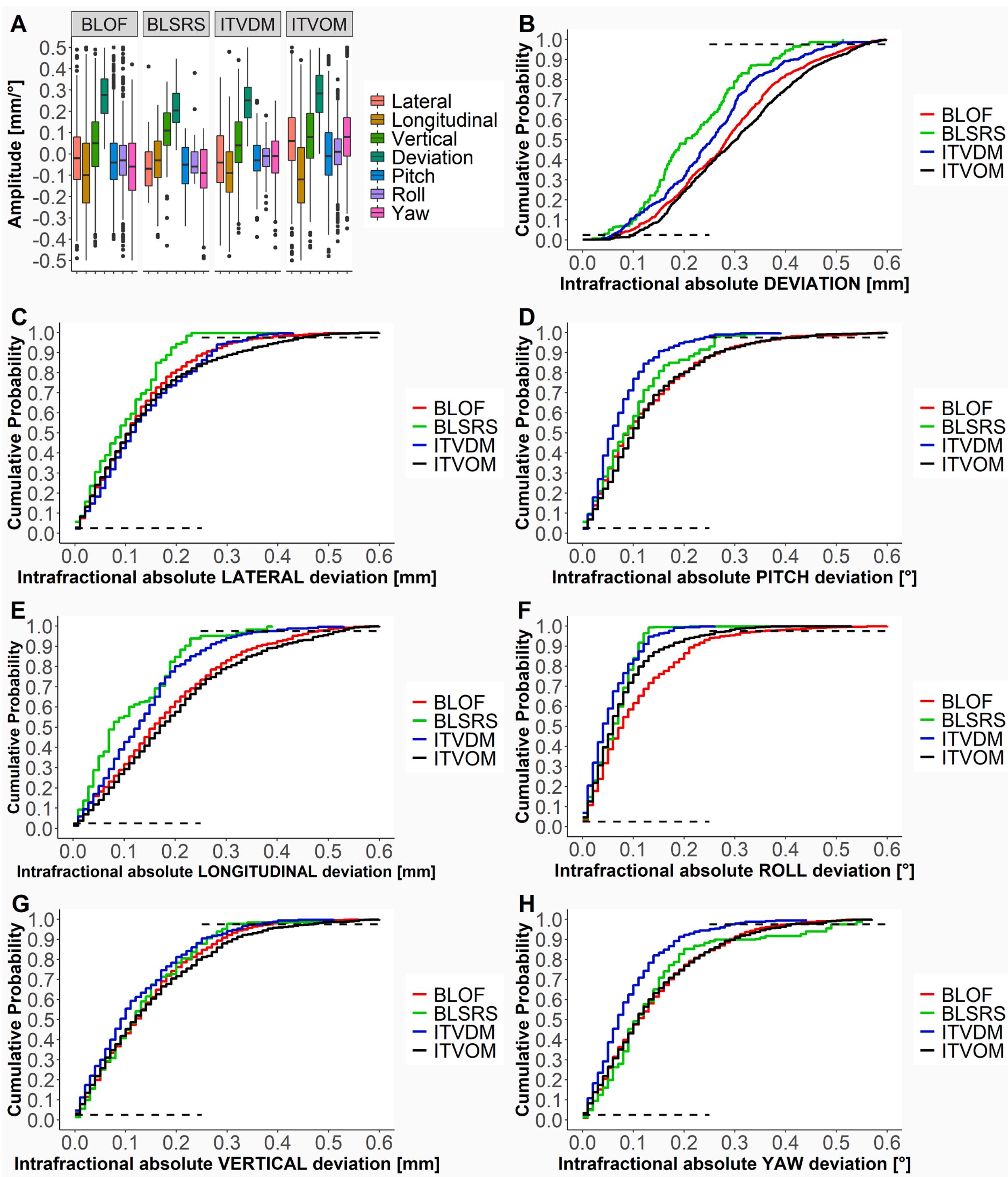

Fig. 1. **A**: Box plots of intrafractional motion in 6 DOF and translational deviation vector for the four different mask systems; **B-H**: Empirical cumulative distribution functions of absolute 6 DOF and translational deviation vector for the four different mask systems; dashed horizontal black lines are showing the lower and upper limit of the 95% confidence interval (n = 40 patients, 3708 stereoscopic images, coplanar configuration).

more beams in general (typically two arcs in coplanar and two arcs in non-coplanar setting and potentially another two arcs for another non-coplanar beam) which results in 10–13 X-ray pairs (non-coplanar arcs are not 360°). This number increases even more, if multiple brain metastases are treated, as these plans typically include 5–8 couch angles.

In the current study we analyzed the intrafractional motion during beam-on time only and the effect of different mask systems on the magnitude of the deviation. The initial deviations during patient repositioning after couch rotations were not evaluated, as they were not during beam on time. This topic will be subject of a further study. However, as the couch position in a non-coplanar setting may contribute to distorting the results of intrafractional movement, we analyzed coplanar and non-coplanar settings separately.

2.4. Statistical analyses

The mean, standard deviation, median and 95%-confidence interval were calculated for the deviations measured for the different masks and spatial axis. As explained above we made a distinction between coplanar and non-coplanar fields. Kruskal-Wallis-tests for independent samples and Dunn-Bonferroni-post-hoc analyses were applied for the comparison of the four different mask systems. Kruskal-Wallis-tests were applied on the absolute values of all seven motion parameters (lateral, longitudinal, vertical, deviation, roll, pitch, yaw) that are shown in Table S1 with an independent sample comparison between the four mask systems. For all statistical analyses a significance level of $\alpha = 0.05$ was defined. MATLAB (R2020b, The MathWorks, Inc., Natick, Massachusetts, United States) was used for data extraction as well as data processing and R 4.1.2 with library ggplot2 and SPSS (IBM SPSS Statistics 24, Armonk, New York, United States) for statistical analyses.

3. Results

3.1. Descriptive analysis

Fig. 1**A** gives an overview of the intrafractional deviations for the four different mask systems in a coplanar setting (see also Table S1). The median magnitude of the deviation vector was generally lower in the coplanar setting than in the non-coplanar setting (except in ITVDM masks). Furthermore, the median was lower in BLSRS (0.2 mm) than in open mask systems or the double mask system (BLOF/ITVOM/ITVDM: 0.3 mm) in the coplanar setting. The same holds true in the non-coplanar setting (BLSRS: 0.3 mm, ITVDM: 0.3 mm; BLOF: 0.4 mm, ITVOM: 0.4 mm).

Outlier analysis for non-SRS treatments showed that the tolerance levels of 1 mm or 1° were exceeded by BLOF-non-coplanar in 0.2% of measurements for roll; by ITVOM-coplanar in 0.1% of measurements for roll and 0.1% of measurements for pitch; and by ITVOM-non-coplanar in 0.4% of measurements for roll.

In SRS treatments the tolerance levels of 0.5 mm or 0.5° were exceeded by BLSRS-coplanar in 1.3% of measurements for vertical and yaw; by BLSRS-non-coplanar in 9.8% of measurements for lateral and 3.7% of measurements for yaw; ITVDM-coplanar in 0.3% of measurements for longitudinal and vertical; ITVDM-non-coplanar in 2% of measurements for lateral, 2.3% of measurements for longitudinal and yaw and 1% of measurements for vertical.

3.2. Mask comparison

Deviations in the lateral axis showed a significant difference between BLSRS and all other masks ($p < 0.05$), with BLSRS yielding the smallest lateral deviations (no difference between BLOF-ITVDM, BLOF-ITVOM and ITVOM-ITVDM), see Fig. 1**B–H.** Similarly, along the longitudinal axis there was a significant difference between BLSRS and all other masks ($p < 0.05$), with BLSRS showing the smallest longitudinal deviations (no difference between BLOF-ITVOM, $p = 0.06$). Vertical intrafractional movement was different between ITVDM and ITVOM, as well as between ITVDM and BLOF ($p < 0.05$), with ITVDM showing the smallest vertical deviation (no difference between BLOF-BLSRS, BLOF-ITVOM, BLSRS-ITVDM and BLSRS-ITVOM). The magnitude of the deviation vector showed a significant difference between all mask systems ($p < 0.05$) with BLSRS yielding the smallest translational deviation, followed by ITVDM, BLOF and finally ITVOM.

Pitch rotation showed a significant difference between all mask combinations except for BLOF-ITVOM. Here, ITVDM had a tendency to yield the lowest pitch deviation. Roll showed a significant difference between all mask combinations except BLSRS-ITVOM. Similarly to the pitch, ITVDM had a tendency for the lowest roll deviation. Yaw rotation showed a significant difference between ITVDM and all other mask systems ($p < 0.05$) except BLSRS. ITVDM had the smallest yaw deviation (no difference between BLOF-BLSRS, BLOF-ITVOM and BLSRS-ITVDM).

The number of stereoscopic images is lower in non-stereotactic masks (BLOF = 7; ITVOM = 6) than in stereotactic ones (BLSRS = 19; ITVDM = 10), suggesting shorter treatment times in non-SRS treatments.

4. Discussion

In the present study, we analyzed the extent of intrafractional motion using four different mask systems during intracranial radiotherapy. We report on patient position deviations recorded from 3708 intrafractional stereoscopic X-ray images in a study population of 40 patients. The results showed that all four different thermoplastic head mask systems lead to standard deviations under 0.3 mm and 0.3° (mean and median lower than 0.2 mm) in 6 DOF and a deviation magnitude of 0.4 mm on average (SD 0.2 mm). Based on a $\pm 2 \times$ SD-interval the deviations are generally smaller than 0.6 mm/0.6° for all mask systems. Although treatment times were longer in stereotactic mask systems (ITVDM, BLSRS) we saw significantly smaller deviations compared to non-stereotactic systems (ITVOM, BLOF).

The ExacTrac X-ray system is an established device for IGRT, with focus on patient positioning in intracranial non-coplanar stereotactic or radiosurgical treatments where CBCT is not feasible [22,23]. ExacTrac Dynamic is an extension with SGRT (optical surface- and thermal-scan) and the successor to ExacTrac X-ray [10].

Badakhshi et al. reported their experience with the ExacTrac X-ray system for intrafractional motion analysis in radiosurgical treatments with thermoplastic masks after every couch rotation by only analyzing the first uncorrected displacement values. The 3D-vector magnitude resulted in a mean value of 1 mm (SD 0.9 mm). Moreover, on average in 12% of measurements the translational deviations exceeded 1 mm [11]. In our analysis the mean 3D-deviation was smaller than 0.5 mm (SD <0.3 mm) in all mask systems and in only 0.2% of all measurements in non-stereotactic mask systems did the 3D-deviation exceeded 1 mm (maximum 1.2 mm).

Lesiuk et al. used the Brainlab mask systems with ExacTrac X-Ray imaging and measured a post-treatment offset of 0.7 mm [12]. Similarly, Shah et al. detected an intrafractional motion using the Brainlab stereotactic mask system of 0.4 mm on average as compared to CBCT-based IGRT [13]. Agazaryan et al. used Brainlab masks for radiosurgical treatments and calculated a mean magnitude of 3D deviations of 0.6 mm ± 0.1 mm [14]. In the present study, we recorded very small intrafractional positioning deviations, and BLSRS resulted in a mean deviation of only 0.3 mm ± 0.2 mm.

Barnes et al. used a mask system which is similar to BLSRS and retrospectively analyzed intrafractional positional variations in stereotactic treatments. The mean deviation along each axis was ± 0.1 mm and ± 0.1°, which is similar to our results for BLSRS mask (±0.1 mm and ± 0.1°) [15].

Tomihara et al. was using CBCT before and after every treatment for intrafractional deviation measurement in double shell mask systems, which lead to an average 3D-deviation of 0.2 mm (SD 0.1 mm), which is also comparable to the results of our double mask system in the coplanar setting (mean 0.3 mm; SD 0.1 mm). As they were comparing two groups of patients with and without mouthpiece they came to the conclusion that the additional usage of a mouthpiece may significantly reduce the interfractional 3D-movement and at least significantly reduce the longitudinal intrafractional deviation. As a disadvantage compared to the present analysis, there were no continuous measurements made during the treatment sessions [16].

Lightstone et al. analyzed the intrafractional deviation with CBCT (pre- and post-treatment) with uniframe thermoplastic masks for brain irradiation resulting in 0.8 mm deviation on average (SD 0.5 mm) which is higher than in non-stereotactic mask systems in the present work (mean 0.4 mm; SD 0.2 mm) [17]. Similarly, Magnesius et al. have observed that the intrafractional head movement during radiotherapy increases over treatment time in all 6 DOF and could show a significant moderate correlation ($r_s = 0.45$) between the time after the first measurement and the extent of 3D-vector motion (from 0.2 mm in the first 2 min to 0.5 mm after 10 min). As we were not able to analyze our data as a function of time, these results may explain why the deviations in non-coplanar setting are significantly higher compared to coplanar setting in all mask systems, as the treatment of patients is always initiated with coplanar beams, and followed by non-coplanar beam configurations [24].

Lewis and collaborators were investigating whether the ExacTrac monitoring frequency of intrafraction patient motion in stereotactic radiosurgery can be reduced. A pre-treatment image was acquired and further images at two time points during the treatment (about 8 and 13 min after first image). They analyzed data sets of 104 patients and did not find a correlation between patient motion over time, in direction or magnitude, and duration of treatment. They came to the conclusion that the imaging frequency could be reduced even further [25].

An important aspect of the present study is the automated gating function of the ExacTrac Dynamic system. If the deviation in 6 DOF exceeds a prescribed tolerance range, the irradiation is stopped automatically without the need of any manual intervention. This rarely happened during beam-on intrafractional monitoring (0.2% of non-SRS cases and 3.6% of SRS cases). Deviations might be significantly higher during patient setup and couch rotations, however this issue was not analyzed and will be subject of a further study. A limitation of the present study is that the sampling rate is not as high in SGRT, since X-ray images are acquired only at certain gantry positions and possible outliers could remain unobserved.

In conclusion, the smallest movements appear in dedicated cranial stereotactic mask systems (BLSRS, ITVDM), which are used for high precision radiosurgical treatments. The evaluation of 487 treatment sessions has shown deviations smaller than 0.6 mm along all translational directions and smaller than 0.6° along all rotational axes using four different thermoplastic mask systems with IGRT. As outliers with a translational deviation of more than one millimeter can occur using open mask systems, open face masks are currently not routinely used in high-dose stereotactic treatments in our clinic.

Ethics Approval and Consent to Participate.

The study was approved by the local ethics committee of the University Hospital, LMU Munich (No. 20–664 ex 09/2020) and registered at German Clinical Trials Register (DRKS-ID: DRKS00025304). Written informed consent was obtained for all patients.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Claus Belka, Philipp Freislederer received research grants and Michael Reiner, Stefanie Corradini, Philipp Freislederer speaker honoraria from Brainlab AG. The other authors declare that they have no competing interests.

Acknowledgement

The authors would like to thank Brainlab AG for their assistance during this project.

Funding

Funding for research with Brainlab ExacTrac Dynamic has been received from Brainlab AG. Brainlab AG was not involved and had no influence on the study design, the collection, analysis or interpretation of data, on the writing of the manuscript or the decision to submit the manuscript for publication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.phro.2022.07.002.

References

[1] Nixon JL, Brown B, Pigott AE, Turner J, Brown E, Bernard A, et al. A prospective examination of mask anxiety during radiotherapy for head and neck cancer and patient perceptions of management strategies. J Med Radiat Sci 2019;66:184–90. https://doi.org/10.1002/jmrs.346.

[2] Li G, Lovelock DM, Mechalakos J, Rao S, Della-Biancia C, Amols H, et al. Migration from full-head mask to “open-face” mask for immobilization of patients with head and neck cancer. J Appl Clin Med Phys 2013;14:243–54. https://doi.org/10.1120/jacmp.v14i5.4400.

[3] Mulla Z, Alwassia RK, Senan EM, Soaida S, Mohamed AAMA, Almerdhemah H, et al. A comparative study between open-face and closed-face masks for head and neck cancer (HNC) in radiation therapy. Rep Pract Oncol Radiother 2020;25:382–8. https://doi.org/10.1016/j.rpor.2020.03.009.

[4] Wiant D, Squire S, Liu H, Maurer J, Lane Hayes T, Sintay B. A prospective evaluation of open face masks for head and neck radiation therapy. Pract Radiat Oncol. 2016. 6. e259-e267. 10.1016/j.prro.2016.02.003.

[5] Pavlica M, Dawley T, Goenka A, Schulder M. Frame-Based and Mask-Based Stereotactic Radiosurgery: The Patient Experience. Compared Stereotact Funct Neurosurg 2021;99:241–9. https://doi.org/10.1159/000511587.

[6] Almeida T, Da Silva CM, Piedade PA, Cordova AL, Bezerra CG, Soboll DS, et al. Positioning deviations in frameless and frame-based intracranial stereotactic radiosurgery. Radiat Phys Chem 2020;167:108363. https://doi.org/10.1016/j.radphyschem.2019.108363.

[7] Schmitt D, Blanck O, Gauer T, Fix MK, Brunner TB, Fleckenstein J, et al. Technological quality requirements for stereotactic radiotherapy Expert review group consensus from the DGMP Working Group for Physics and Technology in Stereotactic Radiotherapy. Strahlenther Onkol 2020;196:421–43. https://doi.org/10.1007/s00066-020-01583-2.

[8] Scaringi C, Agolli L, Minniti G. Technical Advances in Radiation Therapy for Brain Tumors. Anticancer Res. 2018. 38. 6041–5. 10.21873/anticanres.12954.

[9] Ruggieri R, Naccarato S, Mazzola R, Ricchetti F, Corradini S, Fiorentino A, et al. Linac-based VMAT radiosurgery for multiple brain lesions: comparison between a conventional multi-isocenter approach and a new dedicated mono-isocenter technique. Radiat Oncol 2018;13:38. https://doi.org/10.1186/s13014-018-0985-2.

[10] Freislederer P, Kügele M, Öllers M, Swinnen A, Sauer T-O, Bert C, et al. Recent advanced in Surface Guided Radiation Therapy. Radiat Oncol 2020;15:187. https://doi.org/10.1186/s13014-020-01629-w.

[11] Badakhshi H, Barelkowski T, Wust P, Budach V, Boehmer D, Graf R. Intrafraction variations in linac-based image-guided radiosurgery of intracranial lesions. Cancer Radiother 2013;17:664–7. https://doi.org/10.1016/j.canrad.2013.05.011.

[12] Lesiuk MJ, Spencer DP, Chan AK, Voroney J-P, Lau H. Image-Guided Treatment of Fractionated Stereotactic Radiotherapy Patients: A Quantitative Analysis of Pre- and Post-Treatment Orthogonal kV Images of Patients Immobilized with Thermoplastic Masks. J Med Imaging Radiat Sci 2012;43:239–44. https://doi.org/10.1016/j.jmir.2012.07.001.

[13] Shah AP, Meeks DT, Willoughby TR, Ramakrishna N, Warner CJ, Swanick CW, et al. Intrafraction motion during frameless radiosurgery using Varian HyperArcTM and BrainLab ElementsTM immobilization systems. J Radiosurg SBRT 2020;7:149–56.

[14] Agazaryan N, Tenn S, Pouratian N, Kaprealian T. Intra-Fraction Motion Management for Radiosurgical Treatments of Trigeminal Neuralgia: Clinical Experience, Imaging Frequency, and Motion Analysis. Cureus 2021;13:e14616.

[15] Barnes M, Yeo A, Thompson K, Phillips C, Kron T, Hardcastle N. A retrospective analysis of setup and intrafraction positional variation in stereotactic radiotherapy treatments. J Appl Clin Med Phys 2020;21:109–19. https://doi.org/10.1002/acm2.13076.

[16] Tomihara J, Takatsu J, Sugimoto S, Shikama N, Sasai K. Intrafraction stability using full head mask for brain stereotactic radiotherapy. J Appl Clin Med Phys 2021;22:360–70. https://doi.org/10.1002/acm2.13382.

[17] Lightstone AW, Tsao M, Baran PS, Chan G, Pang G, Ma L, et al. Cone beam CT (CBCT) evaluation of inter- and intra-fraction motion for patients undergoing brain radiotherapy immobilized using a commercial thermoplastic mask on a robotic couch. Technol Cancer Res Treat 2012;11:203–9. https://doi.org/10.7785/tcrt.2012.500288.

[18] Zollner B, Heinz C, Pitzler S, Manapov F, Kantz S, Rottler MC, et al. Stereoscopic X-ray imaging, cone beam CT, and couch positioning in stereotactic radiotherapy of intracranial tumors: preliminary results from a cross-modality pilot installation. Radiat Oncol 2016;11:158. https://doi.org/10.1186/s13014-016-0735-2.

[19] Guckenberger M, Baier K, Guenther I, Richter A, Wilbert J, Sauer O, et al. Reliability of the bony anatomy in image-guided stereotactic radiotherapy of brain metastases. Int J Radiat Oncol Biol Phys 2007;69:294–301. https://doi.org/10.1016/j.ijrobp.2007.05.030.

[20] Smyth G, Evans PM, Bamber JC, Bedford JL. Recent developments in non-coplanar radiotherapy. Br J Radiol 2019;92:20180908. https://doi.org/10.1259/bjr.20180908.

[21] Audet C, Poffenbarger BA, Chang P, Jackson PS, Lundahl RE, Ryu SI, et al. Evaluation of volumetric modulated arc therapy for cranial radiosurgery using multiple noncoplanar arcs. Med Phys 2011;38:5863–72. https://doi.org/10.1118/1.3641874.

[22] Jin J-Y, Yin F-F, Tenn SE, Medin PM, Solberg TD. Use of the BrainLAB ExacTrac X-Ray 6D system in image-guided radiotherapy. Med Dosim 2008;33:124–34. https://doi.org/10.1016/j.meddos.2008.02.005.

[23] Sarkar V, Paxton A, Szegedi MW, Zhao H, Huang L, Nelson G, et al. An evaluation of the consistency of shifts reported by three different systems for non-coplanar treatments. J Radiosurg SBRT 2018;5:323–30.

[24] Mangesius J, Seppi T, Weigel R, Arnold CR, Vasiljevic D, Goebel G, et al. Intrafractional 6D head movement increases with time of mask fixation during stereotactic intracranial RT-sessions. Radiat Oncol 2019;14:231. https://doi.org/10.1186/s13014-019-1425-7.

[25] Lewis BC, Snyder WJ, Kim S, Kim T. Monitoring frequency of intra-fraction patient motion using the ExacTrac system for LINAC-based SRS treatments. J Appl Clin Med Phys 2018;19:58–63. https://doi.org/10.1002/acm2.12279.