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PHYSICS CONTRIBUTION

POSITIONING ACCURACY IN STEREOTACTIC RADIOTHERAPY USING A MASK SYSTEM WITH ADDED VACUUM MOUTH PIECE AND STEREOSCOPIC X-RAY POSITIONING

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Purpose: For cranial patients receiving stereotactic radiotherapy, we use the Exactrac stereoscopic X-ray system to optimize patient positioning. Patients are immobilized with the BrainLAB Mask System (BrainLAB, Feldkirchen, Germany). We have developed an adapter to this system that accommodates a vacuum mouth piece (VMP). Measurements with the Exactrac system have been performed to study the positioning accuracy after corrections with this system and to evaluate the accuracy of the VMP vs. the standard available upper jaw support (UJS).
Methods and Materials: Positioning results were collected for 20 patients with the UJS and 20 patients with the VMP, before treatment (1,122 fractions) and after treatment (400 fractions). For all 6 degrees of freedom the average, the random error and systematic error were calculated.
Results: The average vector length before and after correction with the Exactrac system was 2.1 ± 1.2 mm and 0.7 ± 0.6 mm respectively for UJS and 1.7 ± 0.7 mm and 0.4 ± 0.4 mm for VMP. Interfraction positioning for translations was greatly improved after correction with the Exactrac system ($p < 0.0005$) and is better with VMP than with UJS ($p = 0.005$). Outliers were greatly reduced. Interfraction rotations were significantly smaller for VMP. Intrafraction errors for vertical and longitudinal translations and for rotations were smaller for the VMP.
Conclusions: Positioning correction using the Exactrac X-ray system greatly improves accuracy. Adding the VMP results in even better patient fixation and smaller rotations, making it a useful addition to the Mask System. Combined, this is a convenient and accurate alternative to invasive fixation methods. © 2008 Elsevier Inc.

Stereotactic radiotherapy, Radiosurgery, Immobilization, Bite-block, Relocatable frame.

INTRODUCTION

Several systems are used clinically to position and immobilize patients for stereotactic treatments, either for single fraction treatments or for fractionated treatments. Originally only invasive frames were used, and only radiosurgery (single-fraction, high-dose treatment) was applied. The accuracy of these invasive systems is considered to be optimal, as the patient cannot move relative to the coordinate system of the frame. It is argued however, that also invasive stereotactic frames have limited accuracy (1, 2).

Later several noninvasive, relocatable stereotactic immobilization systems have been developed (3–5), mainly to make fractionated treatments possible and to improve patient comfort.

Cranial patients at our institution who are treated at the Novalis (BrainLAB, Feldkirchen, Germany) are immobilized with the BrainLAB Mask System. Based on measurements using the BrainLAB Exactrac system in 9 patients who received fractionated treatment, we concluded that there was room for improvement: we found deviations of up to 3.0 mm in the longitudinal direction and up to 2.5 mm in the other directions, which we considered to be too great for stereotactic treatment. These findings are in agreement with Alheit *et al.* (3) and Baumert *et al.* (6). Therefore we developed an adapter to the Mask System that accommodates for a vacuum mouth piece (VMP, part of the Head Fix system from Medical Intelligence, Schwabmünchen, Germany). The VMP is a customized bite block that is individually molded for each patient and fixed to the palate by applying vacuum.

Our Novalis accelerator is equipped with the Exactrac stereoscopic X-ray positioning system. The Exactrac system can be used to measure the accuracy of patient positioning and to correct deviations.

Exactrac measurements have been performed with patients immobilized with the Mask System with either the Upper Jaw Support (UJS) or the VMP. The UJS is an L-shaped metal

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strip attached to the frame of the mask system that presses against the upper teeth. The UJS is a standard BrainLAB option for use with the Mask System. In this study the VMP system is described and its accuracy is compared to that of the original UJS system. The results of accuracy measurements with these two systems before and after correction with the Exactrac system are presented here. To assess intrafraction stability, measurements were also performed at the end of treatment.

METHODS AND MATERIALS

At our institution, cranial patients treated at the Novalis have always been immobilized using the BrainLAB Mask System. This system consists of a U-shaped frame to which three layers of thermoplastic material are attached. These layers are moulded into the shape of the patients head. In addition to this, an UJS is used, meant to provide a reproducible touch for the patient's teeth (Fig. 1). This should improve the accuracy of patient positioning, especially in the longitudinal direction (6).

Exactrac system

To assess the accuracy of the patient positioning using the mask system, we performed measurements using the BrainLAB Exactrac stereoscopic X-ray system (7). This system uses two fixed X-ray sources and two corresponding image detectors. The images that are taken with this system are registered to digital reconstructed radiographs (DRRs). These DRRs are calculated online (during the registration procedure) from the planning-CT data. Many DRRs are calculated for different small translations in the x, y, and z directions and rotations around the x, y, and z axes. The DRR with the optimal registration result gives the positional deviation for both translations and rotations.

The translational deviation found this way can be corrected by automatic couch movement.

We performed a study, using a human skull phantom with an inserted lead marker, to measure the accuracy of the Exactrac system for this application. The skull phantom was scanned by computed tomography and a treatment plan was made with the isocenter in the center of the lead marker. This isocenter was transferred to the Exactrac system. The skull phantom was positioned in the isocenter and correct positioning was verified using portal film. Well-known position deviations (both for translations and for rotations) were then set up, and the Exactrac result was compared with the actual deviations. This was repeated for several combinations of different translations and rotations. We used translations of approximately 3, 5, 10, and 20 mm and rotations of approximately 2°, 3°, and 5°. This study was similar to that of Verellen *et al.* (7).

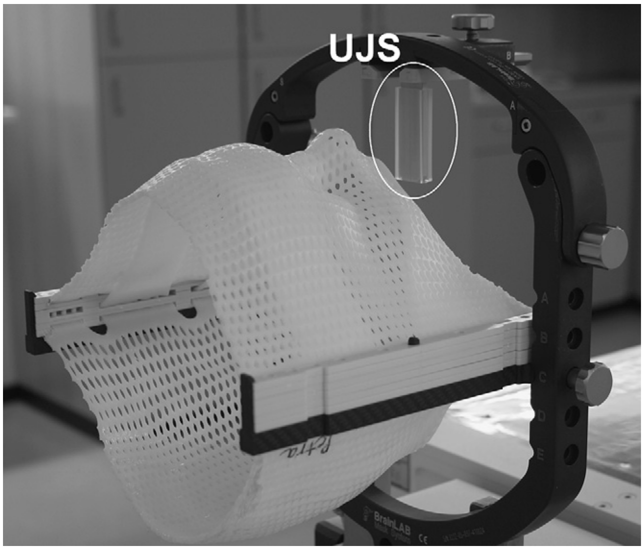

Fig. 1. BrainLAB Mask System with Upper Jaw Support.

Vacuum mouth piece adapter

To improve the positioning, we have developed an adapter to the mask system frame that holds a vacuum mouth piece (VMP). The mouth pieces are obtained from Medical Intelligence. Normally these are used as part of the Headfix system (5).

The adapter was needed because the mouth pieces did not fit directly to the holder for the UJS, which is attached to the U-shaped frame of the Mask System. This gave us the opportunity to incorporate other design goals as follows: a modular design for easy setup; option for rapid assembly; fast release in case of an emergency; incorporation of different degrees of freedom to accommodate for different patient shapes and sizes; and availability of individual, reusable carriages to fix the mouth piece reproducibly in the right position for each patient.

For each patient, an impression of the teeth and the hard palate was made in a dental paste on the mouth piece. Through a small hole, vacuum was applied to the VMP so that it was fixed without the patient actively having to bite to it. The VMP was fixed to the carriage that can be reproducibly positioned in the adapter using a scale.

The mouth piece adapter consists basically of four parts: two identical posts that can be attached to the U-shaped frame of the Mask System using screws (Fig. 2). The main piece of the adapter can be attached to these posts (Fig. 3). This piece is accurately positioned on the posts using indexing pins. With quick releases the piece is secured to the posts. This assures fast and accurate assembly and disassembly. The shape of the adapter is such that enough space is available for the mouth piece itself.

Twelve carriages (in two different sizes) have been manufactured that hold the mouth pieces in such a way that they can be rotated in two different directions and can be moved up and down. When a suitable position is found for a patient, this position can be fixed for the duration of the radiotherapy course. The carriage slides into the adapter and can be moved in the correct position by means of a scale (Fig. 4) and then fixed with a screw.

Vacuum is applied through a thin hose that is attached to the mouth piece at the one end and to a standard suction pump at the other end. A small hole is left in the dental mould to accommodate for the vacuum (5).

When using the VMP, extra attention has to be paid to the fitting of the mask to the upper lip because the VMP uses more space there and the exact position of the head is more critical to make sure that the VMP does not interfere with the target positioner box that is used for initial positioning (see below and Fig. 5).

Positioning study

Positioning results have been collected for 20 patients with the UJS and for 20 patients (with teeth) with the VMP. The patient groups contained similar patients regarding age, tumor, and performance status (Table 1).

Position accuracy was assessed immediately after stereotactic setup, after position correction and immediately after irradiation, to investigate initial positioning accuracy and intrafraction motion.

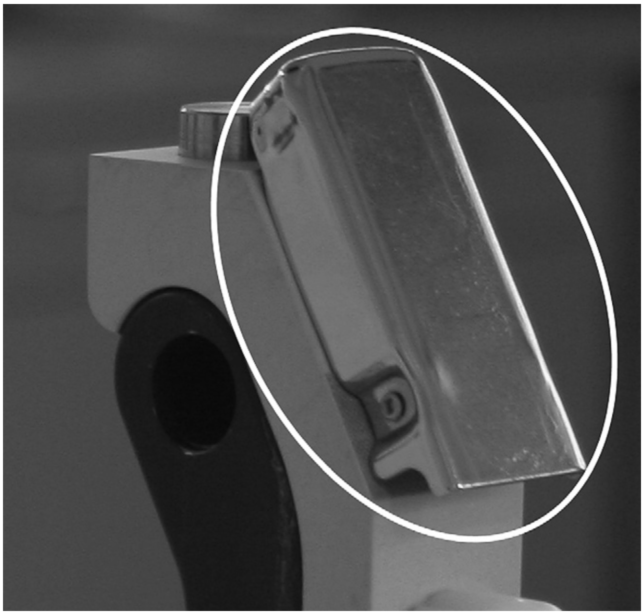

Fig. 2. BrainLAB Mask System with VMP. Attachment of adapter to U-shaped frame. The quick release is indicated in the ellipsis.

The procedure is as follows. Initially patients are positioned based on the target positioner box, on which the isocenter is indicated using printouts of the treatment planning system. After this, Exactrac images are acquired and the position deviation is determined by the Exactrac computer by registering these images to the planning-CT derived DRRs. This result is defined as the initial position deviation. Then the translational part of the position is corrected, if necessary, and a verification is performed, again using the Exactrac system. If the deviations are sufficiently small, treatment is started. Once a week Exactrac images are acquired, and the position accuracy is determined after treatment completion to assess intrafraction movement. Intrafraction movement is defined as the difference between the verification position and the post-treatment position.

For the patients with UJS a total of 616 fractions were analyzed for initial positioning deviation, 392 for verification positioning deviation (after correction), and 192 for intrafraction movement. For the patients with VMP a total of 519 fractions were analyzed for initial positioning deviation, 294 for verification positioning deviation, and 203 for intrafraction movement. There were fewer results for the verification positioning than for initial positioning because not always corrections were required. The threshold for correction was a vector length of 1 or 2 mm, depending on the vicinity of critical structures.

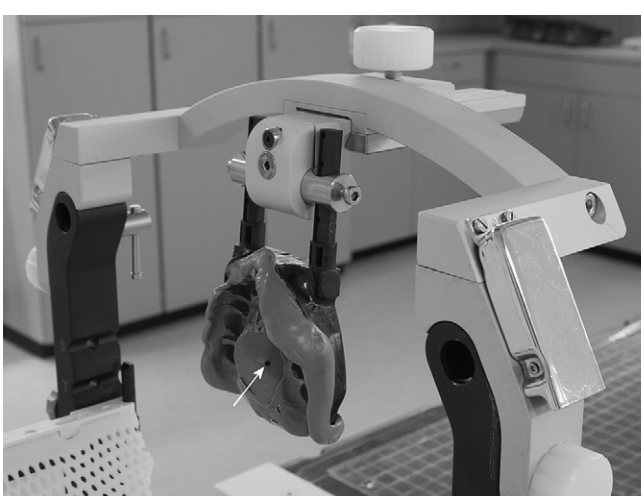

Fig. 3. BrainLAB Mask System with VMP. Adapter with carriage attached to the U-shaped frame. The vacuum hole is indicated by the arrow.

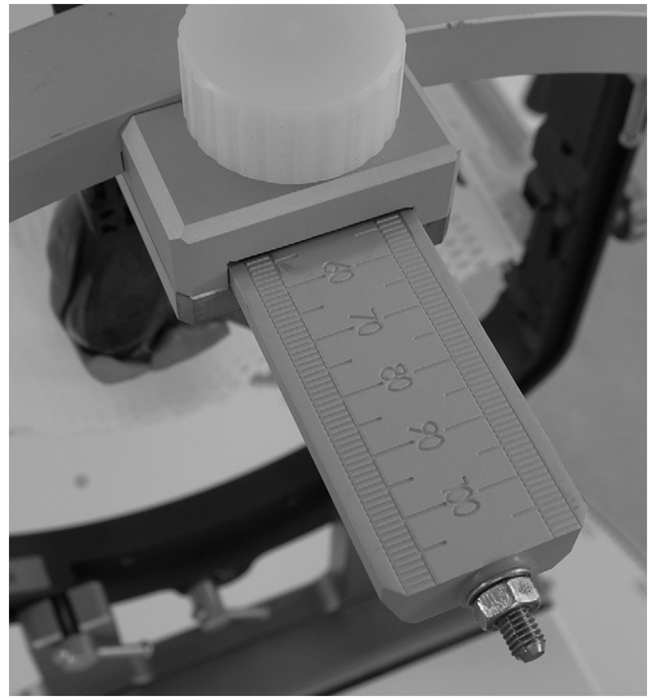

Fig. 4. BrainLAB Mask System with VMP. Carriage with scale.

Several statistical methods have been used in patient positioning studies. In this study we have chosen to analyze the data according to the method of separating inaccuracies in systematic and random errors, according to the method of Bel *et al.* (8), as this method has been shown to give useful results. According to this method, the systematic deviation for a single patient is the mean displacement (relative to the reference position) over all fractions. The random deviation for a single patient is the standard deviation (SD) of the day-to-day variations around this systematic deviation. For a group of patients the systematic error Σ is defined as the standard deviation of the systematic deviations for all patients. The random error σ for a group is defined as the quadratic mean (or root mean square) of the random deviations in the group. A clear description of this method has been published by Stroom and Heijmen (9).

For all 6 degrees of freedom the average over all fractions, the random error and the systematic error were calculated. The results have been analyzed with respect to statistical significance using the *t* test for the averages and for the random errors (σ) and the F-test for the systematic errors (Σ). The *F* test can be used to test whether the SDs of two distributions are equal.

For the length of the displacement vector also the cumulative distribution is calculated, *i.e.,* the frequency of deviations larger than a specific value (vertically) is plotted against that deviation (horizontally).

RESULTS

Exactrac system

Based on the phantom study that we have performed, we have concluded that the maximum deviation of the Exactrac

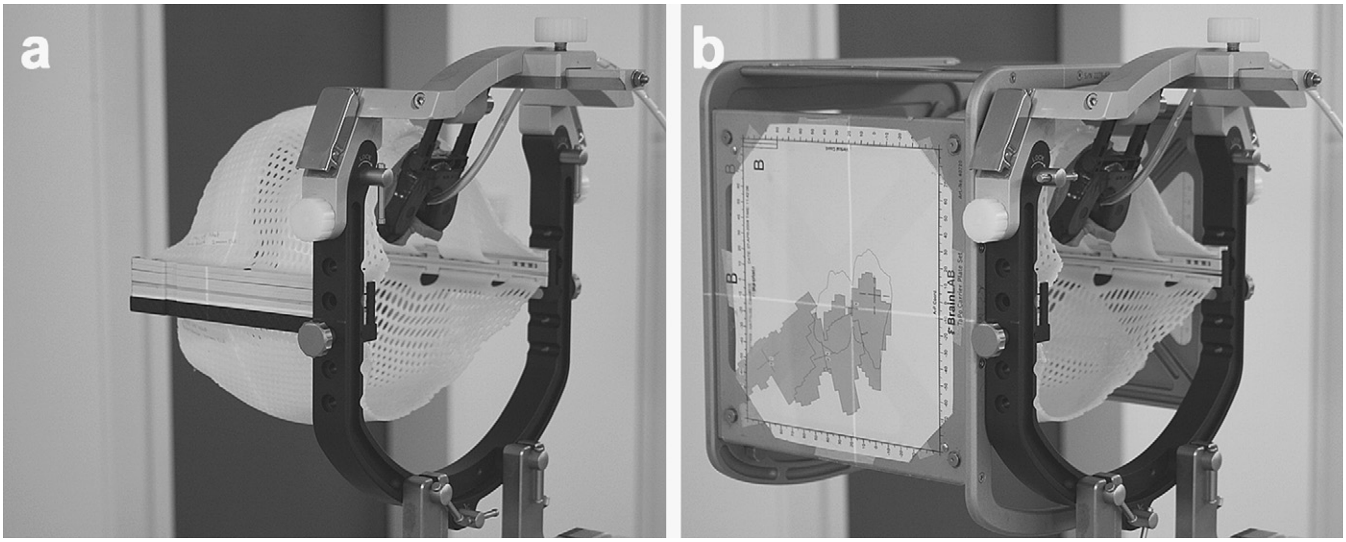

Fig. 5. BrainLAB Mask System with VMP. Overview of the complete setup. (a) Without the Target Positioner Box. (b) With the Target Positioner Box.

system for cranial applications is 0.7 mm in each direction and 0.5° around each axis. For smaller translations (≤5 mm) and rotations (≤3°) accuracy was even better than 0.3 mm for translations and 0.2° for rotations. Overall the RMS value of the deviations for translations in each direction is 0.4 ± 0.2 mm and for rotations 0.2 ± 0.1°. This is slightly better than reported by Verellen *et al*. (7) and Yan *et al*. (10), possibly because of the good contrast of the skull images and because of the fact that their system at that time only used one image detector, attached to the treatment couch. The couch had to be repositioned in between image captures.

Positioning study

The *p* value for the difference in age between the two patient groups was 0.063 and for the difference in performance status 0.176. Therefore we can conclude that there were no significant differences between the groups in this respect. Differences in positioning results between the two patient groups probably cannot be attributed to differences in patient characteristics.

The results of the positioning study are given in Table 2. Differences between the initial positioning accuracy (based on the target positioner box) and on the accuracy of positioning after correction with the Exactrac system were examined.

Table 1. Patient characteristics in study of BrainLAB system with vacuum mouth piece vs. standard upper jaw support

Upper jaw support			Vacuum mouth piece		
Age (y)	Performance status	Diagnosis	Age (y)	Performance status	Diagnosis
72	70	Meningioma	38	100	Meningioma
42	90	Meningioma	46	90	Metastasis
58	90	Glioma	37	100	Glioma
45	90	Trigeminusschwannoma	29	100	Neurocytoma
53	90	Glioma	36	90	Glioma
68	80	Glioma	61	100	Glioma
54	80	Glioma	60	90	Meningioma
57	90	Meningioma	50	90	Glioma
43	100	Pituitary adenoma	36	100	Meningioma
41	70	Glioma	68	90	Meningioma
42	90	Meningioma	78	100	Acousticus neurinoma
52	100	Craniopharyngioma	61	90	Meningioma
61	90	Nasopharynx carcinoma	23	70	Glioma
62	100	Pituitary adenoma	53	80	Glioma
62	90	Glioma	41	80	Glioma
48	90	Acousticus neurinoma	41	80	Glioma
53	70	Pineoblastoma	52	80	Glioma
60	90	Glioma	16	100	Pituitary adenoma
62	80	Meningioma	47	100	Pituitary adenoma
60	90	Glioma	66	90	Pituitary adenoma
Mean 54.8	87.0		47.0	91.0	
SD 9.0	9.2		15.8	9.1	

Table 2. Results of the positioning study

		Initial positioning deviation							Verification images deviation							Intrafraction movement						
		Translations (mm)				Rotations (°)			Translations (mm)				Rotations (°)			Translations (mm)				Rotations (°)		
		Vertical	Long	Lat	Vector	Table	Long	Lat	Vertical	Long	Lat	Vector	Table	Long	Lat	Vertical	Long	Lat	Vector	Table	Long	Lat
Average	VMP	0.40	−0.47	0.58	1.70	0.06	−0.03	−0.42	−0.02	−0.01	0.01	0.43	0.02	0.04	−0.39	−0.03	0.13	−0.11	0.44	0.06	−0.02	−0.02
	UJS	0.46	−0.01	0.69	2.13	0.18	0.21	−0.41	−0.06	0.08	0.05	0.66	0.15	0.22	−0.21	0.01	0.05	−0.11	0.59	0.02	0.02	−0.05
Random σ	VMP	0.48	0.95	0.61	0.69	0.38	0.40	0.38	0.29	0.35	0.30	0.38	0.39	0.43	0.39	0.21	0.30	0.29	0.25	0.27	0.15	0.14
	UJS	0.78	1.47	0.78	1.19	0.80	0.70	0.95	0.41	0.58	0.36	0.58	0.78	0.74	1.01	0.26	0.58	0.28	0.46	0.46	0.49	0.48
Systematic Σ	VMP	0.45	1.08	0.50	0.59	0.49	0.47	0.44	0.17	0.25	0.10	0.20	0.52	0.47	0.49	0.06	0.13	0.16	0.13	0.17	0.15	0.11
	UJS	0.51	1.29	0.86	0.81	0.75	1.03	1.01	0.17	0.46	0.14	0.29	0.76	0.93	1.14	0.10	0.28	0.20	0.17	0.22	0.23	0.31
Range	VMP	−2.4–2.6	−5.8–5.2	−1.8–2.9	0.1–5.8	−2.0–1.8	−1.6–1.6	−2.0–2.0	−1.2–1.5	−2.9–1.8	−1.7–1.4	0.0–2.9	−1.9–1.9	−1.7–1.5	−2.0–2.0	−0.9–1.2	−0.9–1.2	−0.8–1.3	0.0–1.8	−0.7–3.1	−0.6–1.0	−0.5–0.5
	UJS	−2.7–8.1	−6.2–8.9	−2.2–6.6	0.1–10.7	−3.9–10.7	−3.6–4.5	−7.0–2.8	−4.4–2.8	−4.0–4.8	−2.3–2.3	0.1–5.6	−4.0–4.1	−4.7–4.1	−4.5–4.4	−0.7–0.9	−3.1–3.1	−1.4–0.8	0.1–3.2	−1.4–3.1	−4.7–1.5	−2.4–4.0

Abbreviations: Lat = lateral; Long = longitudinal; UJS = upper jaw support; VMP = vacuum mouth piece.
For the underlined numbers, there is a statistically significant difference bewteen the VMP and the UJS.

Positioning improvement by use of the Exactrac system was apparent. Systematic and random errors were in the order of 1 mm for the initial translations and of a few tenths of a millimeter after correction, but the values were smaller for the VMP group than for the UJS group. Both for the UJS and for the VMP the differences between initial positioning accuracy and accuracy after position correction were highly significant for almost all translation parameters: only the average values for longitudinal translations were not significantly different. For the average lateral translations with the UJS the p value was 0.003, for all other parameters the p value was $\leq$0.001. Systematic and random errors for initial rotations and for rotations after correction were approximately 0.4° for the VMP and 0.8° for the UJS. None of the rotational parameters were significantly different between initial positioning accuracy and accuracy after position correction (for all, $p > 0.5$). This makes sense since in this study rotations were not corrected with the Exactrac system. If there were transfer errors between CT, treatment planning and treatment, the average values of translations and rotations would be different from zero. Since these values were all very small, for initial positioning as well as for the corrected positioning and for the UJS as well as for the VMP, we can conclude that there were no systematic transfer errors.

Differences between UJS and VMP concerning inter-fraction positioning accuracy also were evident. For the initial positioning accuracy the differences between the two groups (UJS vs. VMP) were statistically significant for the random errors in vertical and longitudinal translations ($p < 0.001$), the translation vector length ($p = 0.001$) and for rotations around all three axes ($p < 0.002$) and for the systematic errors in lateral translations ($p = 0.025$) and for rotations around the longitudinal and lateral axes ($p = 0.001$). For the positioning after correction the differences were statistically significant for the random errors in longitudinal translations (p = 0.005) and for rotations around all three axes ($p = 0.001$ for rotations around the table axis, $p = 0.004$ for rotations around the longitudinal axis and $p < 0.001$ for rotations around the lateral axis) and for the systematic errors in longitudinal translations ($p = 0.012$) and rotations around the longitudinal ($p = 0.005$) and lateral ($p = 0.001$) axes.

In regard to intrafraction motion, systematic and random errors for intrafraction translations were a few tenths of a millimeter but smaller for the VMP than for the UJS. Systematic and random errors for intrafraction rotations were approximately 0.2° for the VMP and 0.5° for the UJS respectively. The differences were statistically significant for the random errors in longitudinal translations ($p = 0.029$) and for rotations around table ($p = 0.013$), longitudinal ($p = 0.010$), and lateral ($p = 0.001$) axes, as well as for the systematic errors in vertical ($p = 0.041$) and longitudinal ($p = 0.002$) translations and rotations around the lateral axis ($p < 0.001$).

In general, the ranges for almost all VMP parameters were much smaller than for the corresponding UJS parameters.

The cumulative distribution of the displacement vector length was narrower for the VMP than for the UJS, for all three groups of data (Fig. 6). In particular the tail was

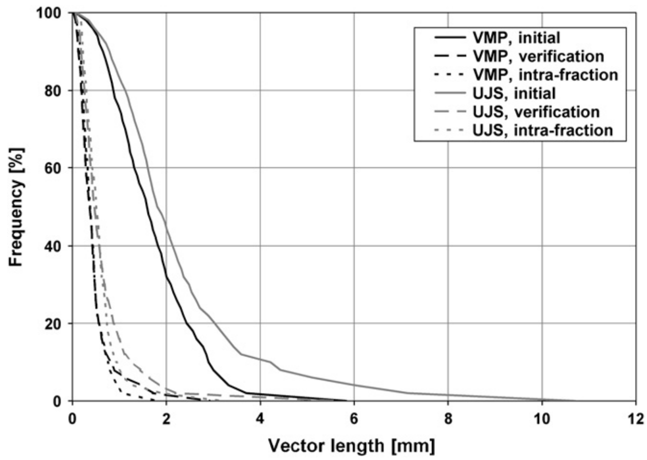

Fig. 6. Cumulative distribution of the displacement vector length.

much smaller, indicating that the number of outliers and the size of the deviation were much smaller. This is in accordance with the smaller range.

DISCUSSION

The analysis shows that the use of the Exactrac system greatly improved patient positioning accuracy, compared with positioning using the target positioner box. Translational errors were much smaller after Exactrac-based correction. Rotational accuracy was not affected.

The results also show that the VMP significantly improved patient positioning, especially with respect to rotations. The initial positioning accuracy as well as the verification positioning accuracy and the intrafraction stability were increased.

Rotations cannot easily be solved without a 6–degree of freedom couch such as the Robotic Table Top (11); therefore the improvement observed for the VMP, both for the initial rotations and for the intrafraction rotations, will be useful. The significance of rotations for fairly spherical brain metastases will be very small (especially if cones are used). However for irregular target shapes such as those seen, for example, for meningiomas, often with adjacent critical structures such as the optic nerves, rotations can be significant, although this remains to be proved dosimetrically.

Even when a Robotic Table Top would be used, an advantage of the VMP is the improved intrafraction immobilization. Another advantage is that the range of rotations is limited with the use of the VMP: no rotations were observed that were greater than 3° (which is the practical limit for Robotic Table Top corrections), as opposed to the values noted with UJS used.

The accuracies found in the present study were of the same order of magnitude as the accuracy of the Exactrac system, which we found to be better than 0.5 mm and 0.5°. This may result in an overestimation of the deviations.

Several studies have been published on positional accuracy for stereotactic treatment, mostly on relocatable fixation systems.

The VMP in the present study originates from the Headfix system (5). Sweeney *et al.* found three-dimensional (3D) vector lengths of on average 1.9 mm (SD, 1.2 mm). These values can be compared with the VMP results for average and σ for the initial positioning deviations of 1.7 mm and 0.7 mm. This suggests that our results were slightly better, probably because of the addition of the mask. Olch *et al.* (12) reported values similar to those of Sweeney *et al.*

Compared with the results of Baumert *et al.* (6), our results for average vector length after initial positioning seem slightly better both for the upper jaw support and for their bite block compared with our VMP. In part this might be caused by the image registration on CT, which has limited accuracy because of the relatively large slice distance of 2 or 3 mm. The VMP accuracy might also be better because of the vacuum, which Baumert *et al.* did not use.

In the study of Engelsman *et al.* (4), several immobilization devices were compared, among others a mask with or without bite block. The interfraction variability in this study was 3 mm in vector length, either with or without bite block, which was considerably less accurate than for both the UJS and VMP systems after initial positioning. These investigators observed a v_{95} (the vector length that was not exceeded in 95% of the cases) of 6.5 mm. In our study, the v_{95} for the VMP and the UJS were 3.2 and 5.5 mm respectively. This is one of the few other studies in which intrafraction variability is investigated. Engelsman *et al.* found for the mask an average vector length of 1.3 mm and a v_{95} of 3 mm, either with or without the bite block. For the VMP and UJS in our study, we found an average vector length of 0.4 and 0.6 mm and a v_{95} of 0.9 and 1.1 mm respectively. Engelsman *et al.* also found, in agreement with the present study, that the largest deviations were seen in the longitudinal direction.

Another study in which intrafraction variability was measured was from Kim *et al.* (13). They used infrared reflective markers, fixed to a bite tray, for this. Their fixation method was a three-point mask. This resulted in a v_{95} of 1.5 mm, compared with our values of 0.9 and 1.1 mm for VMP and UJS, respectively. Therefore use of the mask system with either VMP or UJS seems to improve intrafraction stability.

Rosenthal *et al.* (14) investigated inter- and intrafraction accuracy for a two-point mask system either with or without bite block. They looked at both translations (vector length average and SD) and rotations (SD). Their interfraction translations for the bite block system were slightly larger than ours (after initial positioning), whereas their rotations were comparable. Intrafraction motion was much smaller using the bite block and is comparable to ours.

Compared with other published studies on relocatable fixation methods, we see that our system with the VMP gave results either comparable to or better than most other systems, both for inter- and intrafraction positioning.

The positioning results after correction, measured on the verification images, were very good. We can compare these results to the few studies that have been published on accuracy with invasive frames.

Yeung *et al.* (2) measured positioning accuracy using a geometric test phantom. By analyzing portal films, they found a treatment setup error of 0.73 ± 0.23 mm (average vector length ± 1 SD), which was comparable to the 0.7 ± 0.6 mm that we found for the UJS but considerably larger than the 0.4 ± 0.5 mm for the VMP.

Chang *et al.* (15) evaluated the accuracy of cone beam CT registration for radiosurgery and found an average vector length of 1.3 mm for overall accuracy.

Another invasive fixation method is the Talon frame (16). In this system two screws are inserted in the patient's skull. These are later fixed to a so-called Nomogrip that is attached to the treatment table. This results in an average vector length of 1.4 ± 0.5 mm, which is again larger than our VMP result. The rotations observed (average, 0.2–0.5°) appear to be smaller than with the VMP.

CONCLUSION

To summarize, based on our study results, use of theVMP results in better patient fixation and smaller rotations than the UJS, making it a useful addition to the Mask System. Combined with positioning correction using the X-ray Exactrac system, it is a convenient and accurate alternative to invasive fixation methods.

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