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Original Article

On the Accuracy of Isocenter Verification with kV Imaging in Stereotactic Radiosurgery

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Background and Purpose: Modern medical linear accelerators (linacs) are equipped with X-ray systems, which allow to check the patient's position just prior to treatment. Their usefulness for stereotactic radiosurgery (SRS) depends on how accurately they allow to determine the deviation between the actual and planned isocenter positions. This accuracy was investigated with measurements using two different phantoms (Figures 1 and 2).

Material and Methods: After precisely aligning a phantom onto the linac isocenter, two perpendicular X-rays or a cone-beam CT (CBCT) are taken, and the isocenter position is deduced from this data. The deviation of the thereby gained position from the setup isocenter is taken as a measure for the uncertainty of this method.

Results: Isocenter verification with two orthogonal X-rays (Figure 4) achieves accuracies of better than 1 mm (Table 3). The distance between the isocenters of the CBCT and the linac (Figure 3) is in the order of 1 mm, but remains constant on the time scale of 1 week (Table 1) and may therefore be taken into account. The uncertainty after correction is below 0.2 mm.

Conclusion: kV imaging with the patient in treatment position allows to verify the isocenter position with submillimeter precision, and therefore offers a supplemental test, suitable for SRS, which takes all positional uncertainties into account.

Key Words: Stereotactic · Radiosurgery · Precision · Accuracy · Imaging · Linac · Cone beam

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Zur Genauigkeit der Isozentrumskontrolle mit kV-Bildgebung bei stereotaktischer Radiochirurgie

Hintergrund und Ziel: Moderne medizinische Linearbeschleuniger (Linacs) sind mit Röntgenanlagen ausgestattet, die es erlauben, die Position des Patienten direkt vor der Behandlung zu überprüfen. Ihr Nutzen für die stereotaktische Radiochirurgie (SRS) hängt davon ab, wie genau man die Abweichung zwischen der momentanen und der geplanten Isozentrumsposition bestimmen kann. Diese Genauigkeit wurde mit Messungen an zwei verschiedenen Phantomen untersucht (Abbildungen 1 und 2).

Material und Methodik: Nach präziser Positionierung des Phantoms auf das Isozentrum des Linac werden zwei orthogonale Röntgenbilder oder ein „cone-beam"-CT (CBCT) aufgenommen, aus denen die Isozentrumsposition bestimmt wird. Die Abweichung der so ermittelten Position vom eingestellten Isozentrum wird als Maß für die Ungenauigkeit der Methode angenommen.

Ergebnisse: Isozentrumskontrolle mit zwei orthogonlen Röntgenaufnahmen (Abbildung 4) erreicht eine Genauigkeit von besser als 1 mm (Tabelle 3). Der Abstand zwischen den Isozentren des CBCT und des Linac (Abbildung 3) liegt in der Größenordnung von 1 mm, bleibt aber während 1 Woche konstant (Tabelle 1) und kann somit berücksichtigt werden. Die Ungenauigkeit nach dieser Korrektur ist unterhalb von 0,2 mm.

Schlussfolgerung: kV-Bildgebung mit dem Patienten in der Behandlungsposition erlaubt eine Isozentrumskontrolle mit Submillimeterpräzision und bietet damit einen zusätzlichen Test, der für die SRS geeignet ist und alle räumlichen Unsicherheiten berücksichtigt.

Schlüsselwörter: Stereotaktisch · Radiochirurgie · Präzision · Genauigkeit · Bildgebung · Linac · „Cone beam"

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Introduction

The increasing number of diagnostic imaging tools facilitates a more precise localization of lesions, modern computer technology allows an accurate calculation of dose distributions, which may be minutely applied by state-of-the-art radiotherapy (RT) units. The positioning of the patient relative to the isocenter of the linear accelerator (linac) still is the weakest link in the chain of RT.

In stereotactic radiosurgery (SRS), the requirements for spatial precision are even higher than for fractionated RT, because the lesions are very small, the dose gradients great, and the complete dose is delivered in a single session [16]. Therefore, the patients are treated with their head rigidly bolted to a so-called stereotactic ring, which is screwed to the treatment table. Alternatively the head may be fixated by means of a noninvasive device [16], which is usually the case for fractionated stereotactic radiotherapy (SRT).

The isocenter position is given in stereotactic coordinates that are defined relative to the ring. To overlap the planned isocenter with the isocenter of the linac, a positioning device is attached to the ring, onto which the room lasers are aligned [2]. Various quality assurance (QA) measures performed prior to treatments guarantee that the overall positioning accuracy is around 0.5 mm [4, 7, 11, 16, 17, 19–21].

Utilizing the therapeutic beam to take portals prior to treatment, allows to verify the correctness of the patient's position with millimeter precision [17]. However, since for SRS additional beam-defining devices such as micro multileaf collimators (mMLC) are mounted on the gantry, this procedure is time-consuming, and taking into account the discomfort the invasive fixation means to the patients, portals are often considered impracticable. Modern linacs are equipped with X-ray sources and high resolution at panel detectors, which allows to take radiographs of the patient in treatment position. By rotating the gantry, a volumetric dataset of the patient may be acquired (cone-beam CT [CBCT]) that can be matched with the CT used for treatment planning. Both methods allow to reposition the patient to the intended isocenter [1, 5, 6, 9, 12–14].

X-ray imaging with the patient in treatment position offers the opportunity to verify the final result of the many steps in setting up the patient for treatment. Since each step is potentially error-prone, such a redundant control mechanism is desirable. In order to be able to judge the usefulness of this test, one has to measure how accurate the distance between the linac isocenter and the planned isocenter can be determined.

Material and Methods

Material

SRS has been performed in Freiburg, Germany, for more than 15 years on over 800 patients, focused on the treatment of small cranial lesions. The stereotactic ring from Leibinger (Freiburg, Germany) is used to fixate the patient's head and define the stereotactic coordinate system. The software for treatment planning are Stereoplan (STP) and VIRTUOSO from the same company (Leibinger Freiburg, Germany), which are used for the planning of treatments with circular collimators and mMLC with a leaf width of 1.6 mm at the isocenter, respectively. For quasi-spherical lesions the dose is applied by six arcs of 140° at six different couch positions with circular beam aperture. Irregular volumes are treated with fourteen fixed beams that are individually collimated by the mMLC. For SRS, the standard tabletop is replaced by an extension designed and built in our medical physics engineering laboratory. Its head section includes a fitting for mounting the stereotactic ring, which is movable along all three axes with a resolution better than 0.1 mm and rotatable around the longitudinal and a transverse horizontal axis with resolutions better than 0.01°. Devices are attached to the treatment couch to fixate its position and to suppress the normal motions, except the vertical. With an additional motor the couch may be rotated around the isocenter with a resolution of better than 0.01°.

The measurements were performed with the kV imaging device of an Elekta Synergy (Elekta, Crawley, UK) medical accelerator called XVI, which consists of an X-ray source, an X-ray detector and the corresponding software for image acquisition, reconstruction and fusion. The flat-panel detector has a resolution of 512 × 512 pixel^2 and a dynamic range of 16 bit. The software uses the Feldkamp-Davis-Kress algorithm [3] for CBCT reconstruction and the gray-value matching algorithm by Hristov & Fallone [8].

The Ball Bearing Phantom from Elekta (Figure 1) was used to determine how well the isocenters of the CBCT and the linac coincide. It consists of a metal sphere embedded into a Perspex rod which is attached to a three-dimensional translation stage, which allows an accuracy of positioning better than 0.05 mm. For aligning the phantom onto the room lasers, markings are engraved into the rod's surface. Thereby, the marker sphere may be positioned onto the laser isocenter to

Figure 1. Photograph of the Elekta Ball Bearing Phantom. The metal sphere at the end of the Perspex rod may be positioned precisely with a three-dimensional translation stage. Markers on the surface of the rod allow an accurate alignment of the center of the metal ball onto the room lasers.

Abbildung 1. Foto des Elekta-Ball-Bearing-Phantoms. Die Metallkugel am Ende des Plexiglasstabes kann mit einer dreidimensionalen Verschiebestufe präzise positioniert werden. Markierungen an der Oberfläche des Stabes erlauben eine genaue Ausrichtung der Metallkugel auf die Raumlaser.

within 0.1 mm, as indicated by the standard deviation for the whole measurement (see Table 1).

To test the verification method with two orthogonal radiographs, we used the phantom, which can be seen in Figure 2. Five Perspex rods are screwed between two plates of the same material, four of them building the edges of a cuboid, the last being in its central axis. Inserted into each rod along its central axis every 40 mm are five metal spheres with a diameter of 2.05 mm. When the phantom is attached to the dummy stereotactic ring (see Figure 2), the stereotactic coordinates of the metal spheres are known with a precision of 0.2 mm.

To determine the stereotactic coordinates of the isocenter from two orthogonal radiographs, additional information is needed, which is supplied by a set of localizers [16, 18], that are attached to the stereotactic ring at the front, back, right and left. Each consists of a Perspex tile with a rectangular-shaped metal wire inserted and a metal sphere at each vertex of the rectangle. Stereoplan from Leibinger was used to reconstruct the three-dimensional stereotactic coordinate system from the two-dimensional positions of the localizers' vertices in the two radiographs.

Methods

The coincidence of the linac and CBCT isocenters was measured with the Ball Bearing Phantom. With the room lasers aligned onto the surface markings, a CBCT was taken. The X-ray-opaque ball inside the phantom should appear in the very center of the acquired three-dimensional dataset. Deviations from this position indicate a mismatch between the isocenter, as defined by the intersection of the lasers, and the CBCT isocenter. In order to eliminate influences from the matching procedure, the distance was measured manually with the XVI software, which shows the CBCT isocenter in the sagittal, coronal and transverse slices (Figure 3). Except for the first measurement, three CBCTs with individual alignments of the Ball Bearing Phantom were taken, to check the reproducibility of the data. To gain the quantity of interest, the distance between the linac isocenter and the lasers' intersection point has to be added. This three-dimensional vector is determined as part of our weekly QA program using GafChromic EBT radiochromic film.

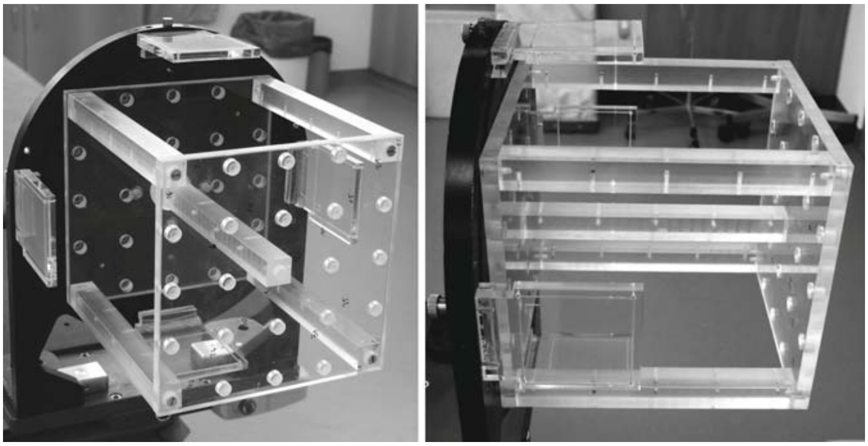
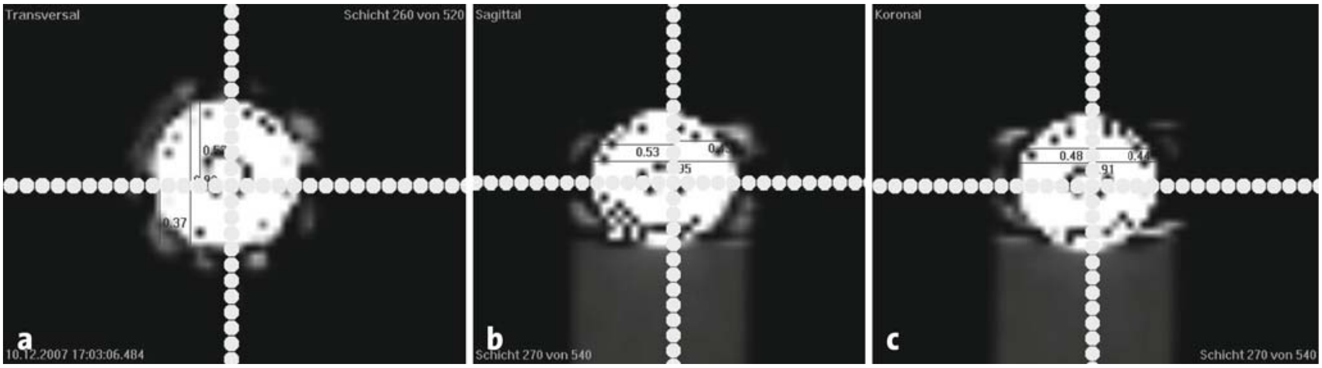


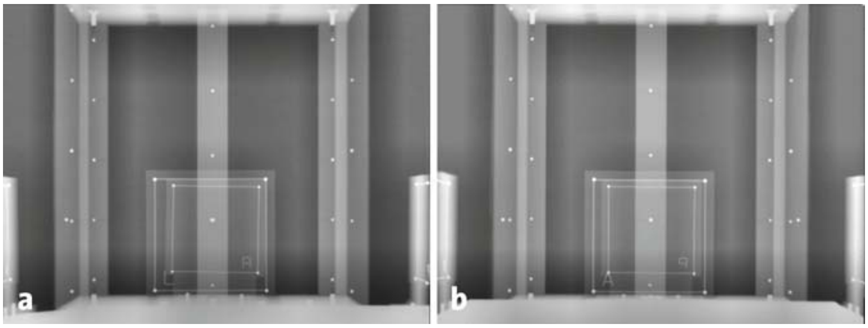
Figure 2. Photographs of the cuboid phantom taken from different angles. X-ray-opaque marker balls are set into the Perspex rods in a regular pattern. At the four sides of the ring, localizers are attached, which are used to reconstruct the stereotactic coordinate system.

Abbildung 2. Fotos des Würfelphantoms aus verschiedenen Blickwinkeln. In den Plexiglasstäben befinden sich in einer regelmäßigen Anordnung röntgenopake Markerkugeln. An allen vier Seiten des Rings sind Lokalisatoren befestigt, die zur Rekonstruktion des stereotaktischen Koordinatensystems benutzt werden.



Figures 3a to 3c. Transverse (a), sagittal (b), and coronal (c) slices of a CBCT of the Ball Bearing Phantom as shown by the XVI software with maximum zoom. The dotted lines mark the CBCT isocenter.

Abbildungen 3a bis 3c. Transversale (a), koronale (b) und sagittale (c) Schnitte eines CBCT des Ball-Bearing-Phantoms, dargestellt mit der XVI-Software bei maximaler Vergrößerung. Die gepunkteten Linien markieren das CBCT-Isozentrum.



Figures 4a and 4b. Radiographs of the cuboid phantom taken from the left (a) and the front (b). The vertices of the localizers are clearly visible, the external markers can be seen within their frame, coinciding with one of the phantom's inner marker spheres.

Abbildungen 4a und 4b. Röntgenbilder des Würfelphantoms, aufgenommen von links (a) und vorn (b). Die Eckpunkte der Lokalisatoren sind deutlich erkennbar, die externen Marker sieht man innerhalb deren Rahmen, sie überschneiden sich mit einem der inneren Marker des Phantoms.

Table 1. Distance between the isocenters of the linac and the cone-beam CT (CBCT), given in millimeters. Except for the first measurement, three CBCTs were acquired and averaged over. These results are listed with the mean value and the corresponding standard deviation.

Tabelle 1. Abstand zwischen den Isozentren des Linac und des „cone-beam"-CT (CBCT) in Millimetern. Außer bei der ersten Messung wurden drei CBCTs aufgenommen und über diese gemittelt. Aufgeführt sind der Mittelwert und die Standardabweichung.

	Day 0	Day 91	Day 95	Day 98
x	0.08	0.20 ± 0.10	0.24 ± 0.07	0.31 ± 0.13
y	1.03	0.38 ± 0.15	0.53 ± 0.19	0.41 ± 0.14
z	0.38	0.23 ± 0.09	0.23 ± 0.03	0.29 ± 0.09
r	1.09	0.51 ± 0.16	0.63 ± 0.19	0.61 ± 0.16

In order to verify the isocenter position with two radiographs taken from perpendicular directions, additional tools are needed to compensate for the reduced amount of information acquired, as compared to the CBCT. Attached to the stereotactic ring are four localizers whose traces in the radiographs are used to reconstruct the stereotactic coordinate system. On the surface of the phantom three X-ray-opaque markers consisting of tungsten spheres are fixed, where the room lasers indicate the isocenter: after the cuboid phantom is positioned, three sheets of paper are attached to it, to create a surface for mounting the isocenter markers, which are fixed with adhesive tape. Radiographs are taken with the X-ray source in 0° and 90° position and subsequently printed with a laser printer onto a sheet of DIN A4 paper each (Figure 4). The positions of the vertices of all four localizers on these two sheets are measured with a digitizer tablet. With this information, Stereoplan deduces all relevant information about the imaging geometry, which is used to define the three-dimensional stereotactic coordinate system. With the two-dimensional positions of the isocenter markers in the radiographs, the three-dimensional stereotactic coordinates of the isocenter are calculated.

Results

In Table 1, the results of measurements of the distance between the isocenters of the linac and the CBCT, taken on 4 different days, are listed. The first CBCT was taken 3 months earlier than the others, which were performed within 1 week. In rows 1–3, the individual components in stereotactic coordinates are listed, the last row shows the length of the displacement vector calculated as $r = \sqrt{x_2 + y_2 + z_2}$. The largest shift observed as measured in three dimensions amounts to 1.1 mm. This value decreases to about 0.6 mm within 3 months to remain constant during the succeeding week. Taking a look at the individual coordinates of the displacement vector reveals that considering the temporal behavior of its length only, is not misleading in this case: the variation in time along each of the three axes of the Cartesian coordinate system is below around 0.6 mm. Also, on the time scale of 1 week, no significant change is apparent. Note that the algebraic sign of each individual coordinate is positive, although these are not absolute values, but real components of a three-dimensional vector.

Taking a closer look at the standard deviations in Table 1 allows to judge the reproducibility. No value exceeds 0.2 mm despite the various sources of error: for each CBCT, the phantom was positioned onto the room lasers, the X-ray source and detector were brought into acquisition position, the three-dimensional dataset was reconstructed from the set of two-dimensional radiographs, and each distance was measured in two orthogonal slices through the CBCT isocenter. The latter induces an additional uncertainty for the directions, which require measurements along and perpendicular to the Perspex rod of the Ball Bearing Phantom (i.e., x and y). Table 2 shows the influence of the choice of slices for measuring. The value in the column labeled "Both" is the average over measurements in transverse and coronal slices for the x-coordinate, and transverse and sagittal for the y-coordinate. For the last two columns, either type of slice is used. The difference in the x-component amounts to 0.14 mm ± 0.03 mm, for the y-component it is 0.26 mm ± 0.01 mm. Although, in general, statistics with a set of only three numbers is hardly significant, the constancy of the difference between transverse and non-transverse slices strongly indicates a systematic effect. In the z-direction, for which sagittal and coronal slices are used, such differences are not observed. The deviation of the isocenter position as determined with two orthogonal radiographs from

Table 2. Distance between the isocenters of the linac and the cone-beam CT (CBCT) for the last three measurements of Table 1, given in millimeters. The mean value and the corresponding standard deviation are listed.

Tabelle 2. Abstand zwischen den Isozentren des Linac und des „cone-beam"-CT (CBCT) für die letzten drei Messungen aus Tabelle 1 in Millimetern. Der Mittelwert und die zugehörige Standardabweichung sind angegeben.

		Both	Transverse	Coronal/sagittal
1	x	0.20 ± 0.10	0.27 ± 0.10	0.13 ± 0.03
	y	0.38 ± 0.15	0.52 ± 0.03	0.25 ± 0.05
2	x	0.24 ± 0.07	0.30 ± 0.05	0.18 ± 0.03
	y	0.53 ± 0.19	0.65 ± 0.13	0.40 ± 0.17
3	x	0.31 ± 0.13	0.40 ± 0.09	0.23 ± 0.10
	y	0.41 ± 0.14	0.53 ± 0.03	0.28 ± 0.03

Table 3. Deviations of the isocenter positions determined with two perpendicular radiographs from their real positions, given in millimeters. The mean value and the corresponding one standard deviation are listed.

Tabelle 3. Abweichungen der Isozentrumspositionen, bestimmt mit zwei orthogonalen Röntgenbildern von den echten Positionen in Millimetern. Der Mittelwert und die zugehörige Standardabweichung sind angegeben.

	Measurement 1	Measurement 2	Measurement 3
x	0.51 ± 0.18	0.02 ± 0.17	–0.06 ± 0.17
y	0.13 ± 0.09	0.65 ± 0.11	0.15 ± 0.07
z	0.46 ± 0.11	0.34 ± 0.07	0.21 ± 0.06
r	0.56 ± 0.16	0.69 ± 0.11	0.61 ± 0.12

its correct position is shown in Table 3 for three different sets of radiographs taken on different days. The standard deviation given for each value results from evaluating the X-rays several times: First, the eight positions of the localizers' vertices in each image are digitized, which yields the transformation into stereotactic coordinates. Then, the isocenter's stereotactic position is determined from its two-dimensional coordinates within the radiograph. Thereby, each time a new transformation is used. The distance from the real isocenter is below 0.7 mm, if one considers the average values, for each of the individual measurement it is below 0.9 mm.

Discussion

Our results show that the stereotactic coordinates of the isocenter can be verified with an accuracy of better than 1 mm by taking two perpendicular radiographs of the patient in treatment position. The process of printing the radiographs with subsequent (re)digitizing of the fiducials' coordinates may contribute to the uncertainty of this method, but we believe it is mainly due to the very simple way, in which the isocenter is marked: metal spheres attached with adhesive tape onto the surface of the phantom or patient, where the room lasers indicate the isocenter position. The evaluation of the radiographs yields reproducible results with a standard deviation of better than 0.2 mm. Multiple evaluations with subsequent averaging may increase the overall accuracy to better than 0.7 mm, which is close to what is generally achieved for SRS. The development of a more sophisticated method for indicating the isocenter in the X-rays will result in an significant increase of accuracy.

Using a CBCT to verify the patient's positioning prior to SRS has the potential to satisfy the requirements on accuracy for this type of treatment: the distance between the isocenters of the CBCT and the linac is in the order of 1 mm, and what is even more important, this distance is reproducible and remains constant on the time scale of 1 week. Therefore, this deviation can be determined as part of the QA program and taken into account by an arithmetic correction. With this correction applied, the uncertainty of the isocenter can be given as the standard deviation for determining the distance between the isocenters, which is below 0.2 mm (see Figure 1).

However, this is only the first step in determining the accuracy of isocenter control with this technique. In order to calculate the distance between the planned and the current isocenter positions, the CBCT has to be matched with the CT, which has been used for treatment planning, because the positions of each of the two isocenters are a priori only known relative to the coordinate system of one of the two CTs. This matching procedure induces an additional uncertainty, whose magnitude we have not investigated for SRS applications yet. In a phantom study, Koehler et al. achieved accuracies between 0.0 mm and 0.9 mm for the gray-value matching algorithm depending on the slice thickness of the planning CT [10]. Oldham et al. found that automatized registration yields correct results to within (0.30 ± 0.28; 0.33 ± 0.21; –0:12 ± 0.30) mm as compared with manual fusion [13], Robar et al. report of accuracies better than 0.5 mm in the transverse directions and better than 0.8 mm for the longitudinal axis [15], Meyer et al. report their whole isocenter test including CBCT acquisition, fusion with the planning CT and automatized patient positioning, to have errors of less than 0.6 mm for matching on bone structures, and less than 0.2 mm for gray-value matching [12]. These results indicate that isocenter verification for SRS with CBCT is possible with the desired precision of 0.5 mm.

Conclusion

We presented two different methods for verification of the isocenter with the patient in treatment position, prior to SRS treatments, using kV imaging modalities. Their accuracy has been evaluated with measurements performed on different phantoms. Both satisfy the requirements and will add a welcome option for a final control, which takes all uncertainties into account. However, we believe these methods cannot replace established QA and positioning procedures, because the latter are prerequisites for achieving high precision: an inexact alignment of the patient with subsequent kV verification requires a thorough repositioning and taking another set of X-rays. In order to reposition the patient with high accuracy, the same methods have to be used, which are part of the current procedure for initial positioning. The methods discussed above are therefore recommended as supplementary tools to verify the correctness of the patient alignment with stereotactic accuracy. Corrections to the patient's position should only be applied if the detected deviations exceed predefined thresholds, in which case the whole setup procedure has to be examined in order to find the cause and take it into account subsequently.

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