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ABSTRACT: The image guidance of a CyberKnife robotic radiosurgery system was quality controlled, including the overall performance of the target locating subsystem and the performance of the x-ray generators and flat panel digital cameras subcomponents. Accuracy and precision of the kV and exposure time settings of the x-ray generators, linearity of the x-ray output, spatial resolution and geometrical distortion of the acquired x-ray images were measured. Total accuracy and precision of the target locating subsystem in defining the position of an anthropomorphic head and neck phantom placed on treatment couch was also measured. Accuracy and precision of the kV as well as exposure time settings and linearity of the x-ray output were found within the acceptance limits suggested in diagnostic radiology. The acquired x-ray images were found to depict the shapes of the imaging objects without any geometrical distortion, being able to resolve differences in the features of imaging objects with critical frequency of 1.3 lp/mm and 1.5 lp/mm for camera A and B, respectively. Total target locating system accuracy was found within 0.2mm and 0.2° in translations and rotations, respectively. Corresponding precision was found lower than 0.5%. These findings render the target locating subsystem of the CyberKnife capable of accurately registering the patient to treatment position and monitoring patient's movement during treatment delivery.

KEYWORDS: Radiotherapy concepts, X-ray radiography and digital radiography (DR), Multi-modality systems, Algoritms and Software for radiotherapy

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Contents

1 Introduction

In stereotactic radiosurgery (SRS), single or multiple fractions of high radiation dose(s) are delivered to a well-defined small intracranial or extracranial target with increased accuracy. SRS has become an important treatment modality in the management of a wide variety of intracranial and, recently, of extracranial lesions, offering the opportunity for a significant reduction of dose to non target tissues with significant benefit to patients. Advances in image guidance and technology opened the way for the development of SRS systems that utilize non rigid immobilization devices to register highly conformal dose distributions with the target without sacrificing the necessary accuracy [1, 2].

In this work the image guidance of a CyberKnife frameless SRS system was quality controlled. The performance of the x-ray tubes and flat panel cameras comprising the Target Locating Subsystem (TLS) as well as the overall TLS performance were evaluated.

2 Materials and methods

2.1 The CyberKnife system

The CyberKnife (Accuray^{TM} Inc., Sunnyvale, USA) SRS system utilizes a six joint robotic arm (KUKA Roboter GmbH, Germany) to manipulate an x-band compact lightweight ($\sim$120 kg) 6MV

Figure 1. The fourth generation CyberKnife® system.

linear accelerator (figure 1). Treatment beam is collimated using twelve circular collimators of 5mm up to 60mm in diameter. The manipulator is paired to a target locating subsystem consisting of two standard diagnostic x-ray tubes and two amorphous silicon flat panel digital cameras, mounted on the ceiling and the floor of the treatment room, respectively. Initial setup of the patient to treatment position and tracking of target movements during treatment, is performed by acquiring a pair of orthogonal x-ray images. The x-ray images are compared with corresponding digitally reconstructed radiographs (DRRs) synthesized from patients computed tomography (CT) scan. The comparison is performed by image registration methods based on bony landmarks of skull for intracranial and spine for spinal treatments or pre-implanted fiducials for extracranial soft tissue targets. Details on the characteristics of the CyberKnife system can be found in literature [1].

2.2 X-ray generators and radiographs quality assurance

2.2.1 Accuracy and precision of the x-ray generators kV and exposure time settings

Consistency of the TLS is based on the high quality of the acquired radiographs, which depends on the x-ray generators' performance. A PTW - DIAVOLT multifunction meter was used to measure accuracy and precision of the kV and exposure time indicators of each x-ray generator. DIAVOLT was positioned at isocenter, facing the under-test tube and performance of both tubes was checked across the CyberKnife clinical practice range values (i.e. 80 kV to 125 kV and 50 ms to 400 ms x-ray generator kV and exposure time values). Accuracy is defined as the deviation of the mean value of the set of experimental measurements from the expected-nominal value. Precision is defined as the deviation of each individual experimental value from the mean experimental value.

2.2.2 Linearity of the x-ray output

X-ray generators are of constant load type with 2.5 mm Al inherent filtration. X-ray output linearity was measured using a diagnostic electrometer connected to a solid state detector with flat energy response and calibrated in diagnostic beams (PTW-DIADOS E electrometer and PTW solid state detector). The solid state detector was positioned at the isocenter facing the tested x-ray tube. A set of exposures was performed for selected kV settings (80 kV to 120 kV). Keeping the exposure time constant at 100ms the exposure (mR) was measured for mAs values ranging from 5 mAs to

30 mAs. Linearity is defined as:

$$\text{Linearity} = \frac{[mR/mAs]_{\max} - [mR/mAs]_{\min}}{[mR/mAs]_{\max} + [mR/mAs]_{\min}}$$

and should be less than 10% [3].

2.2.3 Image quality of the acquired radiographs

The acquired radiographs were measured using two on-floor amorphous silicon digital cameras using a 1024 x 1024 matrix of 0.4 mm pixel size. Primary radiographs suffer from geometrical distortion due to configuration of the x-ray generators and flat panels (the central x-ray beams hit the corresponding cameras with an angle of 45°). This distortion however, is software corrected prior to calculating the position of the imaging object. Image quality in terms of spatial resolution and geometrical distortion of the acquired radiographs was tested using the ETR-1 multi purpose test tool (Scanditronix, Wellhöfer, Germany). The ETR tool was situated at the isocenter, facing the tested generator. A 1 mm thick Al leaf was placed in front of the ETR tool. X-ray images were acquired using typical tube parameters (i.e. 120 kV and 10 mAs). The normalized Modulation Transfer Function (MTF) was calculated using the corresponding feature of the ETR tool and the critical frequency ($f_{50\%}$) that corresponds to 50% relative MTF value was used as a measure of the spatial resolution of both cameras.

2.2.4 TLS accuracy and precision

The acquired radiographs are fed into a 6D target locating software to calculate patient translations and rotations relative to corresponding pre-calculated DRRs. Accuracy and precision of the calculated position was evaluated using an anthropomorphic head and neck phantom. The phantom was initially set up at treatment position and then displaced at different nominal positions on treatment couch. At each position a pair of x-ray images was acquired and the translations and rotations of the phantom were calculated and compared to corresponding nominal displacements. For each position three acquisitions were performed and average translations and rotations of the phantom were obtained. Accuracy is defined as the deviation of the average phantom translations and rotations relative to corresponding nominal displacements, while precision as the standard deviation of translations and rotations. Measurements were performed for the skull, Xsight™ spine and fiducial tracking methods, using corresponding features of the phantom.

3 Results and discussion

3.1 X-ray generator and radiographs quality assurance

3.1.1 Accuracy and precision of the x-ray tube kV and exposure time settings

Accuracy of the kV indicator of each x-ray tube separately was found 8.6% (A) and 6.9% (B) for 80 kV decreasing to 0.4% (A) and 0.2% (B) for 120 kV nominal kV value. Correspondingly, accuracy of the exposure timer was found 1.3% (A) and 1.9% (B) for 50 ms decreasing to 0.2% (A) and 0.3% (B) for 400 ms exposure time nominal values. Precision of both kV and exposure time indicators was found less than 0.2% and 0.3%, for x-ray tube A and B, respectively. Reported

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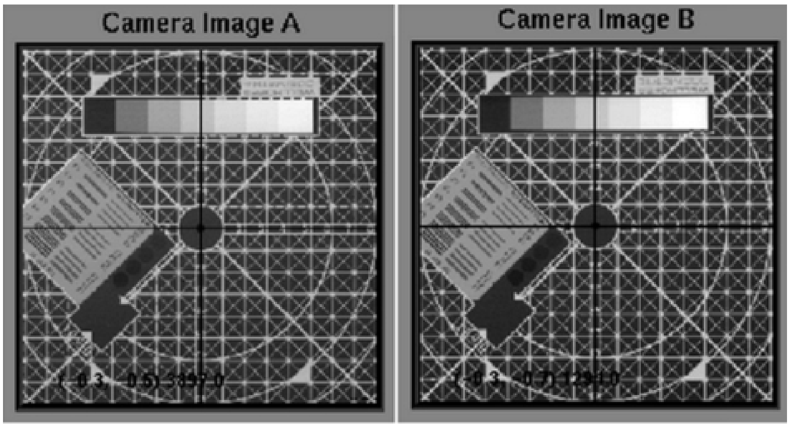

Figure 2. ETR test tool radiographs using camera A and B, respectively.

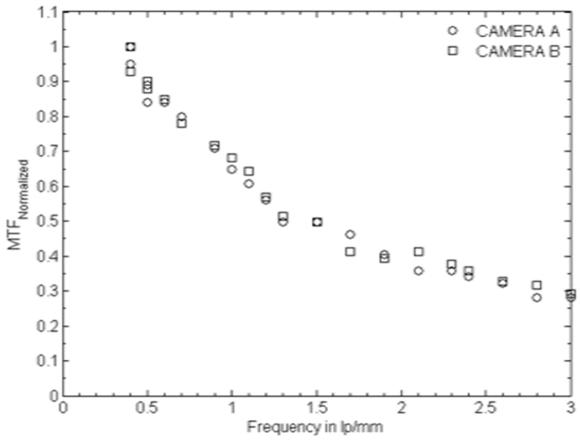

Figure 3. Normalized MTF values for both TLS cameras.

kV and exposure time accuracy and precision results are within the acceptance limits followed in diagnostic radiology [3].

3.1.2 Linearity of the x-ray output

The mean x-ray output averaged on the data of both tubes was found equal to 1.9 mR/mAs for 80 kV, 1.8 mR/mAs for 100 kV and 2.5 mR/mAs for 120 kV, respectively. Linearity of the x-ray output was found less than 6% for both x-ray tubes and the range of the kV nominal values measured, thus lying within the acceptance limits proposed for diagnostic radiology. [3] Taking into account that the above data refer to in-air measurements and assuming a backscatter factor of 1.3 for 120 kV tube voltage [4], 10 mAs per image acquisition and two images per acquisition the total patient surface dose, during a CyberKnife treatment session, is estimated equal to 0.7 mGy per acquisition.

3.1.3 Image quality of flat panel cameras

In figure 2 the acquired x-ray images of the ETR-1 test tool for both cameras, are presented. A general inspection of the presented radiographs reveals a fine depiction of the features of the ETR tool (i.e. lines, cycles) without any observed geometrical distortion. Figure 3 presents' normalized MTF values for both cameras calculated using the corresponding line pattern of the ETR tool. Results show similar MTF values for both detectors presenting a critical frequency ($f_{50\%}$) value of 1.3 lp/mm and 1.5 lp/mm for camera A and B, respectively. The reported spatial resolution is acceptable for image registration purposes and the effect in target positioning calculations is further quantified in the following section in terms of TLS total accuracy and precision.

3.1.4 TLS accuracy and precision

TLS was found capable of defining head phantom position in terms of translations and rotations with an accuracy of 0.2mm and 0.2° respectively for the studied tracking methods. An excellent precision of 0.3% was also observed for the studied tracking methods. These results indicate that setup of patient and monitoring of target movements during a treatment session are measured with an increased accuracy (∼0.2 mm) using skull, Xsight spine and fiducial tracking methods.

4 Conclusions

Image guidance of a CyberKnife SRS system was quality controlled involving x-ray tube parameters, spatial resolution and geometrical distortion of acquired radiographs and total TLS accuracy and precision. X-ray generator parameters where found to lie within the acceptance limits proposed for diagnostic radiology, while the system was found able to resolve differences in the features of the imaging objects of 1.3 lp/mm and 1.5l p/mm for camera A and B, respectively. TLS was found to define the position of the imaging objects with an accuracy of 0.2 mm and 0.2°for translations and rotations, respectively.

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