# Dosimetric and Mechanical Stability of CyberKnife Robotic Radiosurgery Unit: 5 Years' Clinical Experience

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**OBJECTIVE**

The purpose of the present study was to investigate dosimetric and mechanical stability of CyberKnife Robotic Radiosurgery System (Accuray Inc., Sunnyvale, CA, USA) in short- and long-term period.

**METHODS**

Output factor measurements and automated quality assurance (AQA) tests performed on CyberKnife unit 2009-2013 at radiation oncology department of Hacettepe University, Turkey, were analyzed retrospectively.

**RESULTS**

According to the analysis, more than 95% of the output measurements over 5 years were within the tolerance limit ≤2%. In AQA test analysis, 144 AQA test results were within the tolerance limit from 2009 to 2011. However, 7 of the 51 measurements taken in 2012, and 4 of the 47 measurements performed in 2013 exceeded 1 mm radial error.

**CONCLUSION**

Output and AQA data of CyberKnife system indicate that it is quite stable in daily and long-term period. Nevertheless, daily measurements should be performed on CyberKnife unit since high radiation dose per fraction is usually delivered to target volume.

**Keywords:** CyberKnife unit; output stability; stereotactic radiosurgery.

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## Introduction

The main purpose of radiotherapy (RT) is to deliver an accurate absorbed dose to the target volume while staying within acceptable tolerance limits for surrounding normal tissue and critical organs in order to minimize collateral effects. Over the last 2 decades, many improvements have occurred in the field of radiation therapy such as new treatment modalities (intensity-modulated radiotherapy [IMRT], volumetric-modulated arc therapy [VMAT] and stereotactic radiosurgery/radiotherapy [SRS/SRT]), new image-guided systems (in-room computed tomography [CT] techniques, magnetic resonance imaging [MRI]-guided RT and ultrasound [US]-based systems), as well as new quality assurance (QA) and quality control (QC) systems. Nevertheless, there

are still inevitable uncertainties due to the dosimetric and mechanical stability of the linear accelerator (linac) over a period of time. Therefore, efficient QC programs should be put in place to minimize uncertainty based on machine characteristics and parameters.

Dosimetric and mechanical QC of a linac is the process of keeping the accuracy of machine functions within suggested tolerance limits.[1,2] Reports and documents for these suggested values have been published by the International Atomic Energy Agency (IAEA), the American Association of Physicists in Medicine (AAPM), the European Society for Therapeutic Radiology and Oncology (ESTRO), and by several other national and international organizations.[3] The main purpose of all these QA programs is to standardize function of the treatment and measurement equipment used in RT facilities, and thus to maximize quality of patient care. The times tables and tolerance limits of QC for conventional linacs and SRS/SRT units have been studied widely in the literature. [2,4–10] Moreover, control charts, as used in industrial manufacturing and other healthcare systems, have recently been applied to QA for RT to determine short- and long-term stability of conventional linacs.[11–22] However, there does not appear to be a study analyzing short- and long-term output stability of CyberKnife Robotic Radiosurgery System (Accuray Inc., Sunnyvale, CA, USA).

In SRS/SRT facilities with CyberKnife, high radiation dose is usually delivered to target volume with sub-millimeter accuracy. Therefore, both mechanical accuracy and dosimetric stability of the system play important roles in the precision of the treatment. [4] The present study is an analysis of the short- and long-term output and target positioning stability of CyberKnife unit.

## Materials and Methods

### Output stability analysis for CyberKnife Robotic Radiosurgery System

Output measurements collected by department of radiation oncology at Hacettepe University, Turkey, between 2009 and 2013 were analyzed to evaluate the short- and long-term output stability of G4 CyberKnife Robotic Radiosurgery unit. Output was calibrated to 100 cGy=100 MU (or 1 cGy=1 MU) at 1.5 cm depth in water using AAPM Task Group (TG) 51 protocol[23] for reference dose calibration as defined in Table 1. In 5 years, measurements were performed on daily basis

976 times using 0.6 cc PTW Farmer ionization chamber (PTW, Freiburg Germany) with buildup cap attached to the birdcage chamber holder, using necessary correction factors according to AAPM TG-51 protocol (Eq. 1).[23] Measurements were repeated 3 times in every daily setup and average value was taken as output value. When the difference between measured output and reference value exceeded threshold of 2%, output calibration was usually performed before starting the treatment. Readings before and after calibration were recorded in output database.

Equation for the dose absorbed in water for radiation of quality Q is

$$D_W^Q = MN_{D,w}^Q \qquad \text{(Eq. 1) [23]}$$

$D_W^Q$ : Dose in water,

$M$: Corrected electrometer reading

$M$: $P_{ion}$ $P_{TP}$ $P_{elec}$ $P_{pol}$ $M_{raw}$

$P_{ion}$: Correction for incomplete ion collection efficiency

$P_{TP}$: Temperature–pressure correction, which adjusts reading to standard environmental conditions

$P_{elec}$: Correction for electrometer's calibration factor if electrometer and ion chamber are calibrated separately

$P_{pol}$: Correction for any polarity effects

$M_{raw}$: Raw ion chamber reading

$N_{D,w}^Q$ : Absorbed-dose to water calibration factor for an ion chamber

### AQA test analysis for CyberKnife Robotic Radiosurgery System

The AQA test is an isocentric targeting accuracy or robot pointing test to verify delivery accuracy of CyberKnife unit; it is similar to the Winston-Lutz test[24] commonly used in gantry-based SRS/SRT systems. In the present study, 242 AQA tests (from 2009-2013) performed on CyberKnife system at Hacettepe University were analyzed retrospectively. Custom designed AQA phantom containing 2 cm tungsten ball hidden in cubic phantom was used for the measurements (Figure 1). In the QA, 2 orthogonal gafchromic films were placed inside the phantom (Figure 1) and an isocentric treatment consisting of 2 beams in anterior/posterior and lateral directions were delivered tracking 4 fiducial markers (Figure 2). Targeting error (Eq. 2) was determined by analyzing the offset from the center of concentric circles formed by the shadow of the metal ball

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**Table 1**     Reference conditions for output measurement in Cyberknife unit

| Influence quantity | Reference value or reference characteristics |
| --- | --- |
| Phantom material | Water (in daily measurements buildup cap is used with correction factor) |
| Chamber type | Cylindrical |
| Measurement depth $z_{ref}$ | 1.5 g/cm$^2$ |
| Reference point of the chamber | On the central axis at the center of cavity volume |
| Position of the reference point of the chamber | At the measurement depth $z_{ref}$ |
| SSD/SCD | 80 cm |
| Collimator size | 60 mm in diameter |

and the acrylic target sphere in anterior/posterior, left/right and superior/inferior directions. If radial error deviated more than 1 mm from reference value, end-to-end (E2E) tests were performed and the manipulator was recalibrated. All these data were recorded in AQA database.

$$\text{Targeting error}=\sqrt{(offset_{sup-ing})+(offset_{left-right})+(offset_{ant-post})} \quad \text{(Eq. 2)}$$

## Results

### Output stability analysis for CyberKnife Robotic Radiosurgery System

Daily output data of the CyberKnife system is shown



**Fig. 1.**  AQA phantom with 2 orthogonal films after exposure.

in Figure 3. In 2 of 976 measurements, differences with respect to reference value of 100 cGy were more than 3%. However, over 5 years, more than 95% of measurements were within tolerance limits (≤2%). Although percentage of measurements exceeding the limit was nearly 5%, dose calibration was performed in only 2% of the measurements. If limits were exceeded due to a change in ambient conditions, such as room temperature and pressure, calibration was not performed until treatment of first patient, and additional measurements were taken prior to every treatment until stabilization of environment conditions. According to analysis of yearly measurements over 5 years (Figure 3), output of CyberKnife system is quite stable in long-term period. In addition to variation of output trend over time as illustrated in Figure 3, statistical analyses of output values on yearly basis were evaluated, and are presented in Table 2.
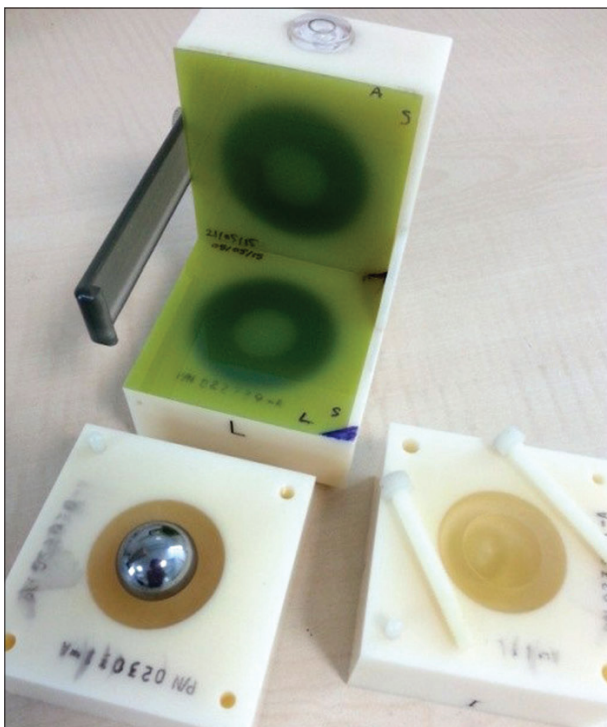
### AQA Test Analysis for CyberKnife Robotic Radiosurgery System

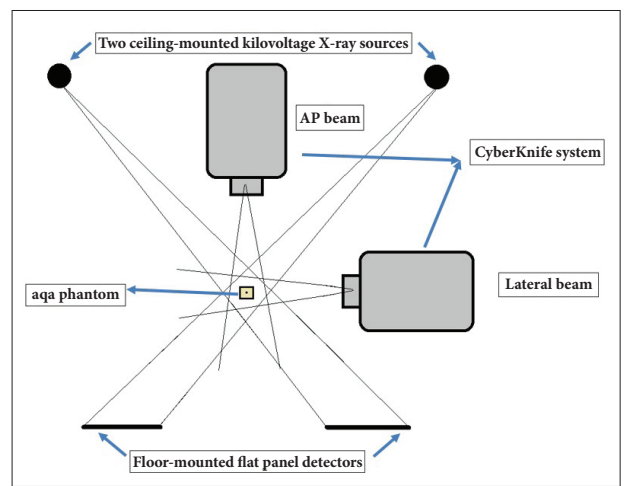Between 2009-2011, 144 AQA tests performed on Cy-



**Fig. 2.**  AQA test geometry in CyberKnife unit.

**Table 2**    Statistical analysis of output stability

| Statistical analysis | 2009 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|
| Mean value (cGy)* | 100.25 | 100.01 | 99.77 | 99.72 | 99.74 |
| Standard deviation (cGy)* | 1.08 | 1.38 | 0.98 | 1.021 | 0.82 |
| Median value (cGy)* | 100.5 | 100.0 | 99.7 | 99.8 | 99.8 |
| Maximum value (cGy)* | 102.4 | 102.9 | 102.5 | 102.8 | 102.9 |
| Minimum value (cGy)* | 96.7 | 96.6 | 97.59 | 97.6 | 98.1 |
| # of measurement | 190 | 209 | 242 | 195 | 140 |
| # of recalibration | 4 | 7 | 5 | 2 | 1 |

*Reference dose: 100 cGy

**Table 3**    Yearly basis statistical analysis of targeting error of CyberKnife system

| Statistical analysis | 2009 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|
| Mean value (mm) | 0.396 | 0.358 | 0.467 | 0.776 | 0.847 |
| Standard deviation (mm) | 0.176 | 0.222 | 0.156 | 0.321 | 0.337 |
| Maximum radial error (mm) | 0.944 | 0.809 | 0.865 | 1.428 | 1.483 |
| No. of measurements exceeding tolerance limit* | 0 | 0 | 0 | 7** | 4*** |
| No. of recalibrations | 0 | 0 | 0 | 1** | 1*** |

*Tolerance limit: radial error <1 mm.

**7 measurements exceeding tolerance limit was performed in May 2012 and manipulator was recalibrated after end-to-end (E2E) test analysis.

***4 measurements exceeding tolerance limit was performed in November 2013 and manipulator was recalibrated after E2E test analysis.

berKnife unit were found to be within the tolerance limit of a radial error of <1 mm. Although 11 of the 98 measurements taken during 2012 and 2013 exceeded the tolerance limit, 7 of 11 measurements were from May 2012 and 4 were taken in November 2013. The manipulator was recalibrated 2 times over 5 years. It can be seen in Table 3 that there is an increasing trend in radial error from 2010 to 2013. Nevertheless, yearly mean radial error variation between consequent years was less than 0.4 mm and maximum targeting error was also less than 1.5 mm over the 5-year period. The present analysis indicates that targeting precision of CyberKnife system on annual basis was under 1 mm (Table 3).

## Discussion

In the literature, there are various studies and suggestions based on long-term clinical experience about the process for and frequency of routine QC checks as well as stability analysis of conventional linacs. Although the working principle and safety aspects of CyberKnife system are quite different from other X-ray based accelerators, there is a limited number of studies about QA procedure and stability of CyberKnife unit with respect to the conventional linacs. Therefore, in the pres-

ent study, we analyzed the short- and long-term output stability and targeting accuracy of CyberKnife robotic radiosurgery system.

The study revealed that output of CyberKnife unit was quite stable based on daily and annual measurements (Figure 3). Almost 5% of measurements exceeded tolerance limits in 5 years. According to our
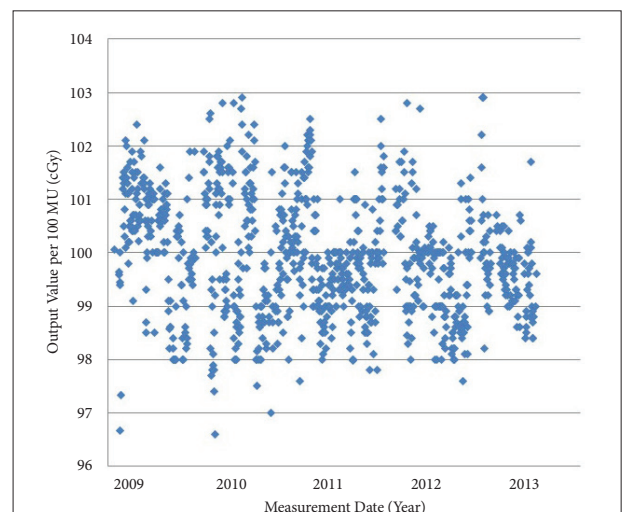
**Fig. 3.**    Daily and long-term output constancy of CyberKnife unit.

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measurement database, a change in environmental conditions had the highest contribution to this variation. Sharma et al.[25] also pointed out that since the CyberKnife uses ion chamber vented to the atmosphere, changes in ambient conditions like temperature and pressure can cause deviation of output value from the baseline. Therefore, output measurements should be performed at least daily, and measurements should be repeated prior to every patient if the ambient conditions change dramatically. In addition to environmental conditions, according to IAEA code of practice TRS-398,[26] user's beam-based factors such as long-term stability of user dosimeter, establishment of measurement setup, dosimeter reading relative to beam monitor, correction for influence quantities and for beam quality cause an uncertainty of greater than 1% in the measurement of absorbed dose to water in reference depth. Therefore, all of these uncertainties should be taken into consideration and several precautions should be taken to minimize the beam-based uncertainty. As a precaution, all measurements should be performed by a licensed medical physicist/medical dosimetrist or a qualified RT technician knowledgeable about CyberKnife QC program. Additionally, dedicated Farmer ionization chamber should be used to minimize detector-based errors and calibration of each detector should be also performed by secondary standard dosimetry laboratory (SSDL) at regular time intervals recommended by international reports. Furthermore, double cross-check should be performed with another calibrated ionization chamber and electrometer if unexpected measurement value is found in order to determine if deviation is due to ionization chamber, electrometer or other factors.

In addition to output stability, SRS/SRT facilities with CyberKnife require high degree of targeting accuracy or mechanical stability with respect to conventional linac-based treatment techniques such as 3-dimensional conformal radiotherapy (3DCRT), IMRT, and VMAT. As small positioning errors in SRS/SRT equipment can result in considerable changes to calculated dose of target volume and affect adjacent critical organs due to steep dose gradient and small target volume. For this reason, effective QC program should be implemented to ensure that the accuracy of the CyberKnife system does not deviate significantly from the baseline. AQA test is useful to check the spatial coordinate system of the manipulator. In addition, detailed analysis of AQA test results can provide valuable information about the short-term and long-term mechanical stability of the CyberKnife unit. In the pres-

ent study, mechanical stability of CyberKnife system on yearly basis was analyzed and results indicated that pointing accuracy of Cyberknife system was well below the tolerance limit of 1 mm, as recommended by AAPM TG-135, between the years of 2009 and 2011. However, 11 of the 98 measurements taken in 2012 and 2013 exceeded tolerance value; 7 were taken in May 2012 and remaining 4 were taken in November 2013. The manipulator, hence, was recalibrated only twice over 5 years. Although, AQA test provide valuable information about targeting accuracy, several parameters should be controlled before each calibration and E2E tests should be performed to ensure whether this deviation is caused by the robot or other factors like film scanner, film displacement and kilovoltage (kV) imaging system.

Overall, analysis showed that output and mechanical stability of CyberKnife was very reliable over 5 years. Nevertheless, daily output measurements and AQA test are strongly recommended by the AAPM TG-135. AQA test is a quick test to evaluate the pointing accuracy of CyberKnife unit. However it has several limitations or disadvantages. The first is that it only provides information on translational parameters (left-right, superior-inferior and anterior-posterior) of the robotic system. Second, it is very costly and time-consuming to take daily measurements. Based on these limitations, AQA tests should be modified by the manufacturer to verify both translational and rotational parameters and a new simple module designed for a quick check of both mechanical and output stability of the system.

## Conclusion

Output data of CyberKnife system is quite stable in daily measurements and in the long-term. In spite of its stability, daily measurements should be performed in SRS/SRT units like CyberKnife Robotic Radiosurgery System since high radiation dose of about 5-34 Gy/fr is usually delivered to target volume. It can be also pointed out that although 11 of 242 AQA tests exceeded the tolerance limit, long-term mechanical stability of the system is reliable, since maximum radial error was below 1.5 mm over 5 years.

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