Design and Development of a Pathfinder Apparatus in an Image-Guided Radiosurgery System

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Abstract

The objective of this study is the design of a novel apparatus (pathfinder) that meets the requirements for efficient quality assurance of beam geometry in a CyberKnife system. CyberKnife is a commercial robotic system of the highest technological sophistication in stereotactic radiosurgery, making it one of the most significant breakthroughs in cancer treatment over the past 30 years. The premise is that a device with such practical implications should be able to provide corrective measures with informed quantitative assessments, including beam angular information to verify the beam targeting accuracy. With the proposed pathfinder, imaging tracking accuracy and consistency can be checked rigorously. An integrated methodology is thus established to reach high efficiency in the testing procedure with coherence between the beam geometry and the pathfinder. The testing procedure is carried out in a real-world environment to demonstrate results with improved feasibility and recorded efficiency.

1. Introduction

CyberKnife is an image-guided stereotactic radiosurgery system capable of treating tumors in the whole body, with the potential for real-time target tracking (Adler et al. 1997, Moharir et al. 1998, Chang et al. 2001 and 2003, and Andrews et al. 2006). The quality assurance has been under ongoing development for rigorous safeguards in managing the treatment process, while seeking the finest precision possible. Since the total clinical precision of the treatment ultimately depends on the accuracy and reproducibility of each CyberKnife beam direction, the necessity of obtaining the full beam geometry is of paramount importance. It is this ultimate goal that this study pursues.

The CyberKnife system consists of following key components: - A robotic manipulator, A light weight linear accelerator capable of producing 6MV X-rays, an imaged guided target localization system, a computer-controlled treatment couch, and Synchrony® target tracking system. The new apparatus (i.e., pathfinder) with two x-ray opaque gold markers and with a predefined separation is designed to be affixed to the CyberKnife lightweight linear accelerator (LINAC). The two radio opaque gold markers are aligned to be parallel to the beam axis with mechanical precision of better than 0.1 mm. This allows for direct visualization of the radiation beam axis through the imaging tracking system's radiographic images. The pathfinder gives a full assessment of the CyberKnife path geometry. In addition, the device can also be used to validate the imaging tracking system consistency by evaluating the distance of the two fiducial markers calculated by the tracking algorithm. The design and the QA principle of the pathfinder encompass the geometry of the pathfinder, the alignment procedures, and testing procedures. In order to define the CyberKnife geometry with the new method developed, five geometric parameters are developed from the new QA procedures. These parameters are off-axis error (position Δ); the Source to Axis Distance (SAD), which measures the distance from the radiation source to the axis of rotation; and the three orientation angles (α, β, γ). With these enumerated parameters, the full assessment of the beam geometry can be achieved.

A prototype was successfully implemented and multiple QA procedures are tested. For each parameter, statistical analyses were performed, and the obtained results are provided. The anticipated advantages of the new apparatus are proven valid; and the imaging tracking system accuracy and consistency can now be measured. We envision a wider range of applications as corrective measures with informed quantitative assessments are now a possibility that clinicians could exploit in their use of the CyberKnife system. The integration of the new apparatus led to the following main contributions: (1) developing and designing a new beam geometry testing apparatus we call the pathfinder, (2) establishing the mathematical relationships to assess accurately the geometry of the apparatus in relation to the CyberKnife beam geometry, (3) representing mechanically the beam's central axis, (4) visualizing the beam's central axis radiographically, and (4) verifying the path geometry in order to proceed with quality assurance (QA) target-locating system (TLS). With the advent of this novel apparatus or pathfinder, clinicians will optimize the critical alignment requirements for an even finer precision through corrective measures and newly available quantitative assessments.

2. Methods

2.1 Pathfinder and Geometry

In this novel apparatus as shown in Figures 1 and 2, the two x-ray opaque gold makers are aligned to be parallel to the beam axis with mechanical precision of better than 0.1 mm. The pathfinder design can be adjusted such that the distance from the X-ray source to the gold marker at the distal end can be precisely known. A treatment plan can be generated to position the LINAC at every node. Images will be taken at each LINAC node position as shown in Figures 2 and 3. With the well specified geometry of the two gold markers and information gained from the radiographic images, the beam orientation can be obtained accurately.

Figure 1. The pathfinder: The tip is made in plastic with two X-ray opaque gold fiducial markers embedded.

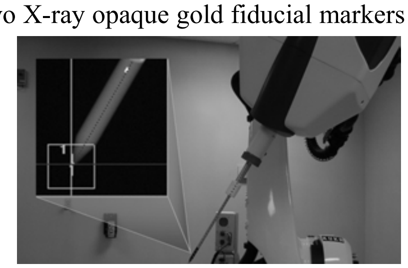


Figure 2. Pathfinder design principles

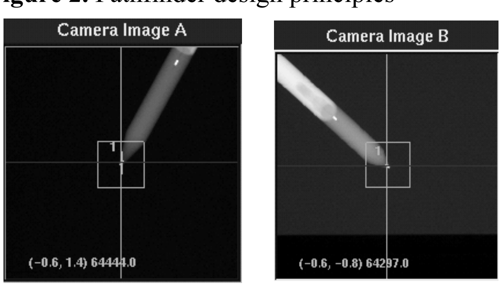


Figure 3. X-imaging graphic taken with the pathfinder mounted on the LINAC

Figure 4 shows the geometry of the pathfinder. In this illustration, F_1 and F2 are the points of the gold opaque fiducial markers. Point F_1 is located at the tip of the pathfinder. The radiation source is denoted by *S*. Points F_1, F_2, S are mechanically aligned. When F_1 is positioned at the CyberKnife's isocenter, the length from *S* to F_1 represents the source to isocenter distance, which is also referred to as SAD.

From the two images acquired from the imaging tracking system. We can locate the two opaque fiducial markers and calculated the coordinates of F_1 and F_2. From the following formulas we can obtain the beam geometry information.

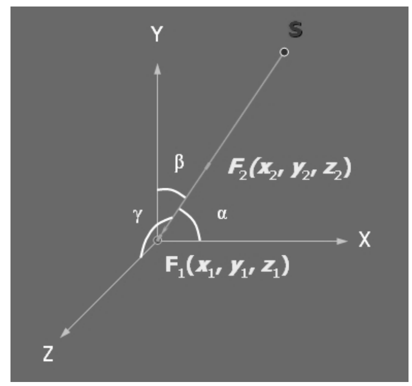


Figure 4. Geometric model representing the relationship of the pathfinder to the physical geometry of the CyberKnife system.

Assuming that the distance $|F_1 - F_2| = d$, and let us denote the 3D directional cosines of the line connecting F_1 to F_2 as ℓ, m, n given by the set of equations in (1):

$$\ell = \cos\alpha = (x_2 - x_1)/d \;;\; m = \cos\beta = (y_2 - y_1)/d \;; \text{and}$$
$$n = \cos\gamma = (z_2 - z_1)/d \qquad (1)$$

The (*x*, *y*, *z*) point of the beam's central axis CAX can be defined by the following slope-intercept equations:

$$x = \ell t + x_1 \;;\; y = mt + y_1 \;;\; z = z_1 + nt \qquad (2)$$

With *t* being a substitutional parameter

The 3D Euclidean distance between the two fiducial markers is computed in the standard form as:

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \qquad (3)$$

Thus we obtain the complete information of the beam geometry including both distal (*SAD*) and angular parameters (ℓ, m, n).

2.2 Pathfinder Alignment

The accuracy of the measurement using the pathfinder relies on the quality of the two gold markers being aligned with the beam axis. During the manufacturing process the alignment of the pathfinder is rigorously tested using a concentricity testing tool, capable of detecting less than 0.1mm eccentricity. In addition, two independent alignment methods are used for verifying and adjusting the alignment of the two gold markers embedded in the pathfinder prior to clinical use.

Alignment Based on Radiation Field: In this method a film is used to first record the actual radiation beam position. The collimator is replaced with the pathfinder. The alignment assessment of the gold markers is realized by comparing the location of the gold markers and the beam as indicated by the exposed film. The method is carried out using the following steps:

1. Affix a GAF chromic film on the table and position the LINAC such that the beam is perpendicular to the table surface, with the source to film distance being 80mm. Use a 5mm collimator (smallest collimator) to deliver 3000cGy (centigray) of cumulative dose to the film (with appropriate buildup). Consequently, a circular darkened area will appear on the film to coincide with the radiation field.
2. Replace the 5mm collimator with the pathfinder, extend the central rod until the first gold marker touches the film. If the pathfinder is aligned with the radiation beam the first gold marker should be situated at the center of the circular darkened area on the film. To further analyze the superposition, the gold marker position is carefully traced on the film.
3. The film is scanned for concentric analysis

Alignment Based on Imaging tracking System: The imaging system can also be used for verifying and adjusting the fiducial markers. With a perfect alignment, the coordinates of the two gold markers obtained by the imaging system should remain constant while rotating the pathfinder. The following are the steps that constitute this imaging-based method:

- Mount the pathfinder to the LINAC.
- Acquire a set of X-ray images of the pathfinder.
- Record the 3D coordinates of the two fiducial markers from the X-ray image set.
- Rotate the pathfinder with x-degree increments, with x being a set value such as 45 or 90 degrees or any other specified value just for alignment checking.
- Image the pathfinder at each position and record the 3D coordinates of the two fiducial markers.
- Compare the data sets by calculating the deviation between them. The lower the deviation the better the alignment of the fiducial markers is.

2.3 Path Quality Assurance

This is to assure the consistency of the node geometry over the course of time (Schroeder 1992, Dybkaer et al. 1993, Almond et al. 1999, Zupancic and Bajd 1998, Mehta et al. 2002, Ryu et al. 2001, Murphy 2004, Inoue et al. 2001, Shiomi et al. 2000 and 2001, Wong et al. 2004, Accuray Inc. 2007, and Gerszten et al. 2003) . Baseline beam geometric parameters are obtained immediately after the path calibration. The pathfinder is used periodically to access the consistency of the beam geometric parameters.

2.3.1 QA Plan. In order to verify the predefined node geometry, a QA plan is generated with all the beams set at their default orientation. This is done with the fiducial tracking mode having a single marker as the tracking fiducial and having the imaging center coinciding with the marker. The isocentric plan is then generated with the planning isocenter falling on the imaging center. Figure 5 shows the configuration of such a QA plan

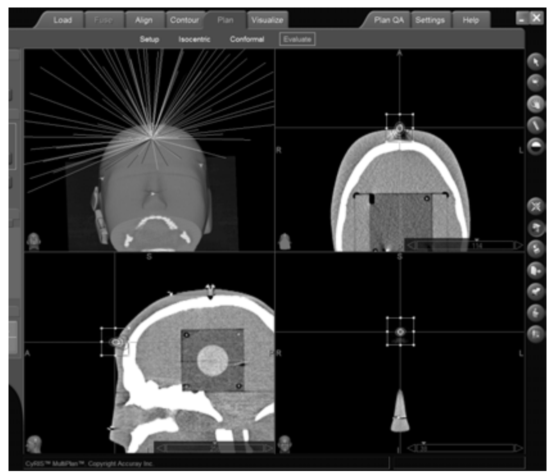
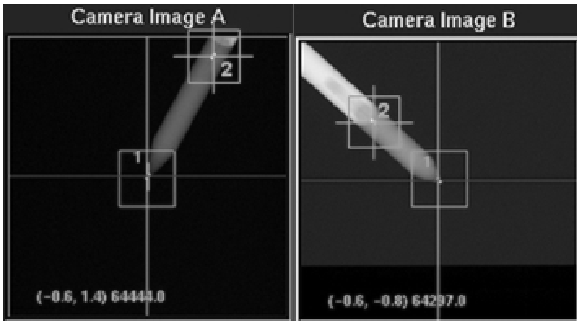


Figure 5: Testing plan: A single isocentric planning with beams converged at a fiducial marker.

Test setup. The test setup involves the following steps:

- Transfer the QA plan to the treatment delivery system.
- Set the length such that the distance from the most distal marker will be the same SAD as the QA plan when the pathfinder is attached to the LINAC
- Initiate the QA plan using the imaging system to locate a reference fiducial at the imaging center with a minimized position error (less than 0.1mm).
- Remove the reference fiducial to prevent collisions during the test.
- Proceed with the simulated treatment of the QA plan from this point on the manipulator will position the LINAC to all the preprogrammed nodes sequentially.

2.3.2 Path Finding. At each node position the images are acquired and the coordinates of both fiducial markers are obtained and recorded as shown in Figure 6.



(a) X-ray radiographs of the pathfinder: Fiducial 1 located at the distal end of the pathfinder.

(b) Geometry coordinates by the imaging system

Figure 6. X-ray radiographs of the pathfinder and its geometry through imaging tracking system.

In reference to Figure 7, the key parameters sought can now be computed

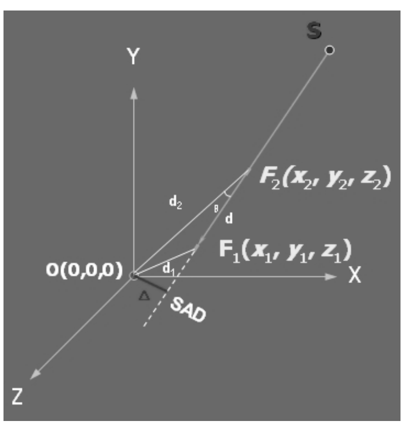


Figure 7. Off-axis beam geometry, illustrating the condition when the distal marker is not located at the system's iso-center O (0,0,0).

Assuming that the distance between O and F_1 is denoted as d_1, and the distance between O and F_2 be denoted as d_2. The beam off-axis error, position Δ can then be calculated using following equations:

$$\Delta = d_2 \sin\theta, \quad (4)$$

where,

$$\sin\theta = \sqrt{1 - \left(\frac{d^2 + d_2^2 - d_1^2}{2dd_2}\right)^2} \quad (5)$$

The actual SAD can be calculated as:

$$SAD = SAD_0 + \left(\frac{d^2 + d_2^2 - d_1^2}{2d} - d\right) \quad (6)$$

$$SAD\Delta = SAD - SAD_0 = \frac{d^2 + d_2^2 - d_1^2}{2d} - d \quad (7)$$

SAD_0 which is the distance between point S and F_2, is the predefined SAD for the node. The assessment of the consistency of beam geometry is accomplished by analyzing the consistencies of all the above parameters.

3. Results

Using the method described herein a pathfinder prototype was designed and applied for path assessment using the CyberKnife system. A total of 55 nodes were measured. The data taken from 10 measurements were processed to obtain the beam's geometric parameters, namely the off-axis error (position Δ), the source to isocenter distance (SAD) and the three angles of the beam axis. The results presented in this study focus on the consistency aspect of QA analysis. The objective is to verify the stability of the path geometry.

3.1 Pathfinder Alignment

Each time before its use, the pathfinder alignment is carried out using the radiation-field-film exposure method. Figure 8 shows a GAF chromic film exposed to 3000cGy using a 5mm collimator at a source-film distance of 800 mm.

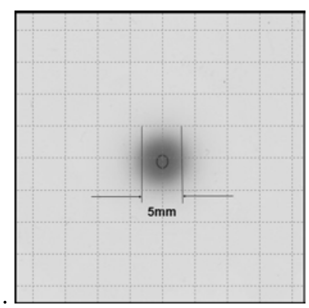


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Figure 8. The GAF radio-chromic film exposed using 5mm collimator at 3000cGy; the red line is the contour of Fiducial 1.

A mark was made on the film indicating the position of the most distal gold fiducial when the pathfinder was attached to the CyberKnife LINAC. The film is processed to verify the quality of the pathfinder alignment by studying the concentricity of the radiation field shown on the film and the mark of the distal fiducial. The alignment is then further tested with the system's orthogonal guiding radiographic images. The central rod is continuously adjusted until the coordinates of the two gold markers show no variation, while the pathfinder is rotated around the collimator fixture.

3.2 Imaging Tracking System

Consistency of the imaging tracking system can be demonstrated by repeatedly acquiring images of a fix fiducial array. Table 1 shows the coordinates of the two markers generated by the imaging tracking system, 30 times, with the LINAC positioned at one node. This demonstrates an excellent linearity of the imaging tracking system. The results show that at a single node position, the readouts of both fiducial 1 and fiducial 2 are constants. The differences are in the range of 0.2mm. Two similar tests are done at another two node positions No.26 and No.36. Results show that a 0.25mm difference at *X*, *Y*, *Z* coordinates occurs occasionally during the treatment simulation. The linearity of the imaging system is further verified by analyzing the consistency of the calculated distance between the two gold markers (*d*) at different node positions. The mean value of the distance is 68.75mm. From a 55 imaging set, we obtain a standard deviation of 0.189.

Table 1: A 30-time exposure from a single pathfinder node position, showing deviations between coordinates

Node	Fiducial 1			Fiducial 2		
16	Xo	Yo	Zo	X1	Y_1	Z_1
1	3.0	-1.1	-0.1	66.2	-28.4	-1.9
2	3.0	-1.1	-0.1	66.2	-28.4	-1.9
3	3.0	1.0	-0.1	66.1	-28.4	-1.9
4	3.0	-1.1	-0.2	66.2	-28.4	-1.9
5	2.9	-1.1	-0.1	66.2	-28.5	-1.9
6	3.0	-1.0	-0.1	66.2	-28.4	-1.9
7	3.0	-1.1	-0.1	66.2	-28.4	-1.9
8	3.0	-1.1	-0.1	66.2	-28.4	-1.8
9	3.0	-1.1	-0.1	66.1	-28.4	-1.9
10	3.0	-1.1	-0.1	66.2	-28.4	-1.9
11	3.0	-1.1	-0.1	66.2	-28.4	-1.9
12	3.0	-1.1	0.0	66.2	-28.4	-1.9
13	3.0	-1.0	-0.1	66.2	-28.3	-1.9
14	3.0	-1.1	-0.1	66.2	-28.4	-1.9
15	3.0	-1.1	-0.1	66.3	-28.4	-1.9
16	2.9	-1.1	-0.1	66.2	-28.4	-1.9
17	3.0	-1.1	-0.1	66.1	-28.4	-1.8
18	3.0	-1.1	-0.2	66.2	-28.4	-1.9
19	3.0	-1.1	-0.1	66.2	-28.4	-1.9
20	3.0	-1.1	-0.1	66.2	-28.4	-1.9
21	3.0	-1.0	-0.1	66.2	-28.5	-1.9
22	3.1	-1.1	-0.1	66.2	-28.4	-1.9
23	3.0	-1.1	-0.1	66.3	-28.4	-1.8
24	3.0	-1.1	-0.1	66.2	-28.4	-1.9
25	3.0	-1.1	-0.1	66.2	-28.4	-1.9
26	3.0	-1.1	0.0	66.1	-28.4	-1.9
27	3.0	-1.1	-0.1	66.2	-28.5	-1.9
28	3.0	-1.1	-0.1	66.2	-28.4	-1.9
29	3.0	-1.1	-0.1	66.2	-28.4	-1.9
30	3.0	-1.1	-0.1	66.2	-28.4	-1.9
Standard Deviation	0.031984	0.382731	0.037139	0.044978	0.036515	0.030513

3.3 Path Geometry Assessment

The QA plan used for testing consists of 55 nodes. A total of 10 tests were performed. The geometric parameters were derived for each node. These parameters are off-axis error (position Δ), SAD deviation (SADΔ), and three orientation angles (α, β, γ).

Figure 5.2 shows the position Δ of all 55 nodes from 10 measurements. The standard deviation bars are presented. This can be compared with a hypothetical ideal situation, in which every beam axis is supposed to pass through the isocenter, with a null position Δ. In reality residual position delta exists for all beams, which will inevitably contribute to the total inaccuracy. A systemic correction is implemented in our system to minimize the total system error. This requires that the position Δ for each beam should remain unchanged. The tests after establishing the baseline indicate such constancy has been satisfied. Should a noticeable change in position Δ of any node be observed, a corrective action must be followed to either restore all the 5 parameters (α, β, γ, *SAD*Δ, position Δ), adjusting as a consequence the systemic correction to reassure the total sub-millimeter accuracy?

Experiments reveal that:

(1) *SAD*Δ may not have a predictable correlation with the position Δ. We observe a maximum *SAD*Δ of about 4mm, although for every node the position Δ has shown reasonable consistency. In the present system the variation on the dose distribution resulting from deviations in *SAD* is not corrected, a *SAD*Δ of 4mm can result in the dose delivery variation of about 1%.

(2) Minimized standard deviations of the α, β, γ angles indicate the consistent quality of the robot manipulator. It should be noted that a change in one of these angles will result in changes of the beam entry path in the patient. However with the quantitative assessment of the angular information which can be used to adjust the CyberKnife path, along with the two distal parameters, position Δ and SAD Δ, the accuracy in the beam entry path is guaranteed.

4. Conclusion

At this technological juncture, prior to the development of the pathfinder, from the experiments conducted, it is noted that even a minimum position Δ does not guarantee the accuracy of SAD or the beam's angulations. It is worthy to emphasize that the position Δ alone is insufficient to guarantee the desired accuracy, and only when it is taken with the beam's SAD and angular orientations would they together affect the total clinical accuracy. Although a systematic correction can be introduced as a final measure to reduce the total clinical error, it was stated earlier that in order to minimize the total clinical error, every factor that can potentially contribute to the total clinical error has to be individually minimized. Among all the factors that affect clinical accuracy the path geometry is considered as crucial. However without full information of the path geometry it is impossible to effectively evaluate the consistency of the path geometric parameters and to realistically minimize its error. The pathfinder thus offers this unique advantage in resolving this dilemma.

One additional advantage of the pathfinder is its integrated nature. Since the testing procedure is carried out based on the imaging tracking system, the information obtained from a test would reveal a composite effect from both the robotic movement and the imaging tracking quality, especially, the reconstructed distance between the two fiducial markers from all nodes. This last fact provides indispensable means of evaluating the linearity and accuracy of the imaging tracking system. It is apparent that the pathfinder can be an effective tool to calibrate the path, since it provides the complete beam geometry information.

The significance of this study is that it addresses the deficiency of the current testing method in order to improve the quality and efficiency of the testing. Consequently, the quality control for the CyberKnife beam orientations can be carried out with the required frequency, in situation when the beam orientation needs adjustment, while the corrections can be easily done with quantitative information to yield optimal accuracy. This will further assure an effective treatment delivery with an affirmative clinical outcome. In retrospect, the CyberKnife is an integrated system with multiple components, each contributing to the total treatment outcome. In order to assure the accuracy that leads to a consistent clinical outcome, every component needs to be tested periodically to safeguard against potential deviations in accuracy. Naturally, the accuracy of the beam orientation is of primary importance.

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