Accurate Proton Beam Localization

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Abstract— *The goal of this work was to further improve an experimental proton radiosurgery system at Loma Linda University Medical Center to reach sub-millimeter accuracy before proton radiosurgery with narrow beams can be used in a clinical trial. Radiosurgery precisely targets a specific anatomical region with high doses of radiation. We have developed a program that provides correcting translational offsets during target rotation and allows the proton beams to be aimed at the target from multiple directions in the proton research room. This was accomplished by developing and testing advanced image analysis software tools. The targeting accuracy was determined with a commercial stereotactic performance phantom. It was found that sub-millimeter targeting accuracy can be achieved with the current system.*

Keywords: localization, proton radiosurgery, stereotactic target localization, image analysis, sub-millimeter targeting accuracy

1. Introduction

Stereotactic radiosurgery (SRS) is a radiation therapy method that precisely delivers very high dose of external radiation to well-defined targets in the brain or to the target within the body. SRS has many advantages over open surgery. Since there is no incision with this method, there is no risk of bleeding, infection or other possible surgical complications. [2]

Functional radiosurgery is a sub-specialty of SRS that creates small lesions in an area of diseased brain that interrupts pathological functions, such as abnormal movement or pain, one can treat functional disorders. Diseases that are currently treated with functional radiosurgery include, trigeminal neuralgia, Parkinson's disease and essential tremor.

The use of protons for functional radiosurgery will be advantageous when the lesion is in close proximity to critical neural structures. The methodology for functional proton radiosurgery is currently being developed at Loma Linda University Medical Center (LLUMC). With a margin of error of 1-2 mm, there is a high risk of delivering a dose to the incorrect location, which could result in serious complications for the patient. Working in such close proximities to critical brain features provides very little margin for error. Therefore, a very accurate method for stereotactic target localization must be developed and tested prior to deployment of a new system for functional proton radiosurgery in human patients. An experimental platform for testing these new methods has been built and is used to develop and test new methods of beam localization and verification.

Previous work centered on methods for accurately aligning the target to the proton beam using feedback from a room-fixed camera-based system [3], [4], [5]. The primary goal of the present work was to test a different strategy to improve proton beam targeting accuracy for proton functional radiosurgery by using a system that relies on accurate characterization of 3D-stage movements and rotation relative to a fixed proton beam.

An important task within the work, described in this paper, was to develop an algorithm that will deliver proton beams from multiple directions to the target without the need for checking correct alignment before each beam delivery. The performance of the algorithm was verified by analyzing radiochromic films embedded in a quality assurance phantom (Lucy®, Standard Imaging Inc.). In addition, development of a user-friendly software interface was an important subject of the present research work.

2. Approach

2.1 Experimental Setup

Unlike the proton treatment rooms at LLUMC with their 90-ton, three-story gantries that can be rotated 360 degrees to deliver the proton beams at any angle prescribed by the physician, a research platform for phantoms and small animals (rats) was built and mounted on one of the fixed horizontal proton beam lines that deliver the proton beams through evacuated steel tubes (beam pipes) into the proton research room.

The research system simulates the functional proton radiosurgery treatment, which in the future will take place in one of the proton treatment rooms. The stereotactic setup consists of one rotational and three translational micro-stages (Newport Corporation). The rotational stage rotates the

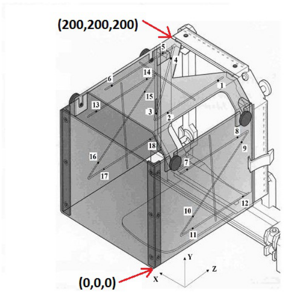

Fig. 1: Leksell coordinate frame and Leksell CT indicator frame.

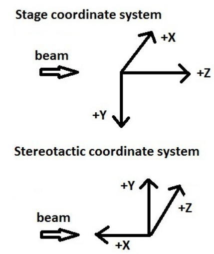

Fig. 2: Coordinate system of micro-stage and stereotactic coordinate system.

stereotactic system [1] around an axis that is approximately parallel to the z axis of stereotactic system, thus, simulating the rotation of the proton beam around the gantry axis in the treatment room. The translational stages align the target to the beam axis in longitudinal, horizontal and vertical direction. The program developed within this research is able to control the rotational micro-stage, acquire the position of the target from the stereotactic localization software, and to perform translational moves to bring a preselected target into alignment with the beam axis. The performance of this system was tested using the Lucy phantom.

2.2 Stereotactic and Stage Coordinate Systems

The main goal of this research was to develop and test methodology to accurately align the proton beam to a planned target in a stereotactic coordinate system.

The stereotactic coordinate system is defined by the Leksell coordinate frame (Electa), an instrument often used for clinical stereotatic radiosurgery, and the CT-indicator frame, which used with computed tomography (CT) to define the stereotactic coordinates of the target (see Figure 1). The stereotactic coordinate system is a right-handed Cartesian system. When the Leksell coordinate frame is mounted on a human head, the positive x-axis points from the patient's right to the left, the positive y-axis from the back of the head to the nose, and the positive z-axis from head to feet. The Leksell coordinate frame is engraved with a rectilinear coordinate scale, in which the origin (0, 0, 0) is located superior, lateral, and posterior to the frame on the patient's superior right side. The coordinates are expressed in millimeters. The center of the Leksell CT indicator frame is at stereotactic coordinates (100, 100, 133) mm.

The stage coordinate system is defined by three orthogonal translational stages, which move the stereotactic system relative to the beam axis. Imagine one stands in front of the stage system and the proton beam comes from the left side, refer to Figure 2. The positive x-axis (longitudinal translational stage) coincides with the stereotactic z-axis, the positive y-axis points to the opposite direction of the stereotactic y-axis, and the positive z-axis points to the opposite direction of the stereotactic x-axis.

In the proton research room, the radiosurgery cart is aligned to the proton beam line. When correctly aligned, the proton beam line passes through the center of the Leksell CT indicator frame, which has stereotactic coordinates (100, 100, 133) mm and stage coordinates (-6.5, 39.5, 0) mm.

2.3 Alignment Software

In order to relate the stereotactic coordinates of a target and corresponding micro-stage coordinates that will align the proton beam to the target, a software algorithm which takes into account the different orientation and relative position of these two systems was required. Assuming the stage coordinates of the home position are (h1,h2,h3) and the corresponding stereotactic coordinates are (s1,s2,s3). The following transformation performs this task.

$$matrix = \begin{bmatrix} 0 & 0 & 1.0000 \\ -0.0034 & 1.0000 & 0 \\ -1.0000 & -0.0034 & 0 \end{bmatrix} \quad (1)$$

$$vector = (h1, h2, h3) - (s1, s2, s3) * matrix \quad (2)$$

$$(h1, h2, h3) = (s1, s2, s3) * matrix + vector \quad (3)$$

To prevent a user from accidentally changing the main program, the home position coordinate and the associated stereotactic coordinates are stored in an external text file. The beam axis was carefully aligned to the stereotactic coordinate system so that it is parallel to the stereotactic x-axis, represented by the vector (-1,0,0). The translational stages can only be moved from -50 mm to +50 mm in x- and z- direction and from -8 mm to +93 mm in y direction. In order to detect whether the movement is beyond these limits, the program first calculates all required translational corrections and validates them against the limitations. If any correction is beyond the translational limits, the user is alerted with a warning message. The translational corrections along the beam direction (z-axis of the stage system) are ignored to prevent collision of the object with the collimator. The color code for "Off limits"(stage could not performed move) and "Error"(stage did not reach destination) is red;

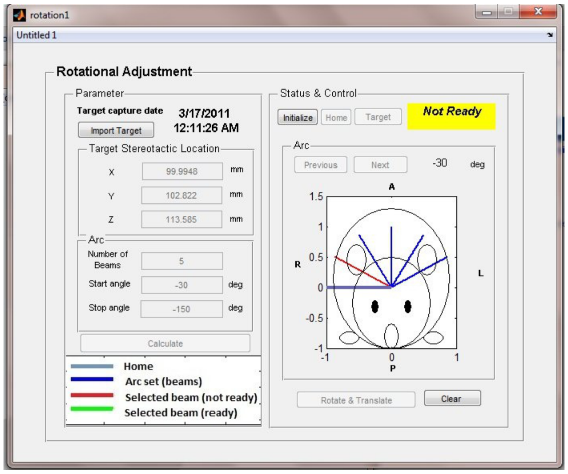

Fig. 3: Rotational system GUI.

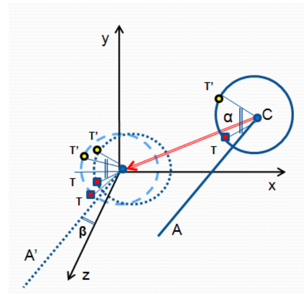

Fig. 4: Geometry of the mathematical steps to perform a target rotation by angle α around a micro-stage axis A.

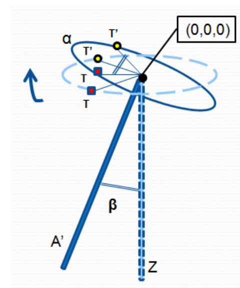

Fig. 5: Once the micro-stage rotational axis has been shifted to the origin, it needs to be aligned with the stereotactic z-axis before applying the 2D rotation by angle α.

the color code for "Not ready"(moves not yet complete) is yellow, and the color code for "Ready"(all moves completed) is green.

The input parameters of the alignment software includes stereotactic target coordinates, the number of beam angles, and the start and stop angles, so that all the beams can be rapidly delivered in sequence. The software was written to that the user can go to the preselected beam angles in arbitrary sequence. In the home position, the rat is in the orientation shown in Figure 3. This corresponds to an absolute internal rotation of +90 degrees. The stage can rotate counterclockwise only up to an angle of -170 degrees and clockwise up to +360 degrees (a total of 530 degrees range). In order to perform the stage rotation from the home position by an angle of ϕ degrees, the stage needs to be programmed to rotate to an absolute angle of ϕ + 90 degrees if $\phi >$ -260 degrees and ϕ + 450 degrees otherwise. The GUI shows the beam location relative to the rat, refer to Figure 3. Legend of beam indicator: The beam location at home position, usually at 0 degrees, is indicated by a grey line; the pre-set beam angles is indicated by a blue line, and the selected beam line is indicated by a red line, and once the system is ready changes to a green line.

2.4 Method to Calculate Translational Corrections

This section contains a mathematical description of the translational corrections required after the rotation has been made, one needs to perform a mathematical 3D rotation and calculate the 3D vector that shifts the rotated target point back to the beam axis. In case the rotational axis is parallel to the z-axis, only a 2D rotation in the xy-plane is required and the correction vector becomes a 2D vector.

A 3D rotation describes the motion of a rigid body around a fixed axis in 3D space, while a 2D rotation describes the motion of a rigid body around a fixed point in a 2D plane. It is mathematically convenient to perform a 3D rotation about any axis in space by first making the rotational axis coincide with one of the axes of the coordinate system and then to perform a 2D rotation about that axis.

In the present experimental setup, the rotational micro-stage axis is only approximately parallel to the z-axis of the stereotactic reference system. To calculate a 3D rotation of the target point T around the rotational micro-stage axis A by an angle α mathematically, one first shifts the axis point C that has the same z-coordinate as the target point to the origin of the stereotactic reference system. The rotational axis A' now intersects the origin, but is still rotated by the angle β relative to the z-axis, see Figure 4. The next steps are to align the rotational axis A' with the stereotactic z-axis and then to apply the 2D rotation with angle α, see Figure 5.

One now needs to find the translational vector that shifts the target point back to the fixed beam axis. Instead of rotating the target point, one can also rotate the beam axis, keeping the target point fixed, see Figure 6. The translational correction is represented by the vector $v3$ which shifts the target point back to the beam axis. The components of this vector should be expressed along the axes of the translational stages which perform the translational corrections. When performed correctly, a series of rotated beam axis should intersect at the target point, forming a star pattern.

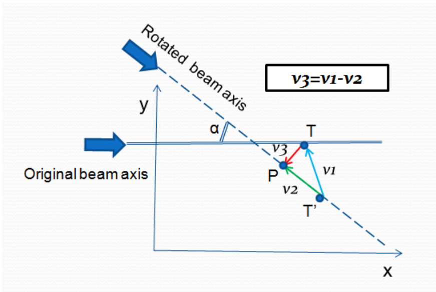

Fig. 6: Geometric representation of the translational correction. The beam axis is rotated by angle α relative to the target point T. After rotation, the point on the beam axis originally intersecting T is now T'. P is the projection of T onto the new beam axis. The translational correction $v3$ is calculated as shown.

A program was developed implementing an algorithm that calculates the translational corrections in the stage coordinate system. The algorithm initially assumed that the z-axis is the rotational axis at the beginning, but the result was not ideal. The stereotactic coordinates of the rotational axis were further defined by another experiment and image analysis. The details of this will be published in the thesis of one of the authors. With the defined rotational axis, the structure of the algorithm of the translational corrections is as follows:

1) Find the point on the rotation axis that intersects the xy-plane containing the stereotactic target point (i.e., has the same stereotactic z coordinate). Since the z-axis is practically perpendicular to the xy-plane, the intersection point will be the point on the axis closest to the target.
2) Find the translation vector that shifts the point found in step 2 to the origin of the stereotactic reference system (SRS) and shift the beam axis point (target point) by adding the same vector to the coordinates of the target point.
3) Find the 3D rotation matrix MA that aligns the horizontal rotation axis with the stereotactic z-axis and apply this rotation to the beam axis point and vector.
4) Perform the stage rotation for a given angle by using a 2D rotation matrix in the xy-plane and apply it to the beam axis point and beam axis vector.
5) Apply the inverse rotation matrix MA and then the inverse translation vector to the shifted and rotated beam axis point and vector found in step 4. This will represent the new beam axis location in the SRS coordinates system.
6) Find the vector that represents the shortest distance from the stereotactic target point to the beam axis and convert its components to correctional shifts of the translational stages by applying the reverse rotation matrix.

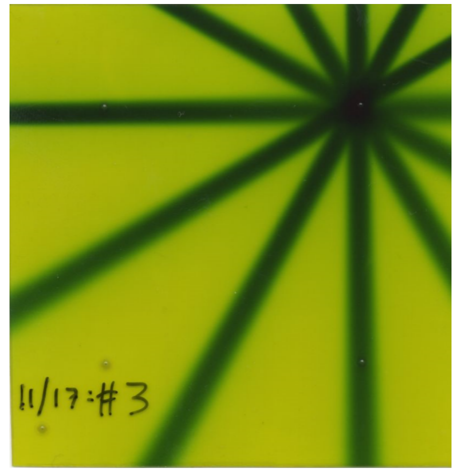

Fig. 7: Six beams from 0 degrees to -150 degrees, aiming at the upper right pin of the Lucy phantom cassette. The location of the marker pin is also visible on the film.

3. Performance Study

To verify the stereotactic targeting accuracy, narrow proton beams were imaged with a radiochromic film (Gafchromic EBT2 film, International Specialty Products), embedded in the Lucy phantom and to find the beam axis in relation to target points, also visible on the film. The 5 steel pins of 0.5 mm diameter, which hold the radiochromic film in place were used as stereotactic targets. The advantage of using these targets was that they could be seen in CT localization images and also created visible perforation holes in the film. An image analysis method was developed to support the data analysis of the performance study.

Each proton beam produces a dark footprint with lateral penumbra on the radiochromic film. In order to digitize the beam image meaningfully and efficiently, the intensity image was converted to a binary image. Then the MatLab Canny Edge Detector was applied to define beam edges in the beam penumbra by looking for local maxima of the intensity gradient of the image. Once the two edge lines of each beam path were found, the beam axes equations were determined by averaging parameters of the edge lines.

In addition to finding the beam axis, it was also necessary to define the location of target pins on the film, which were represented by small pin holes. Besides from serving as target points, they can also be used to determine the length scale (pixel per mm) of the digital image, as four of the five pins in the Lucy phantom form a square with 40 mm side length.

4. Conclusion

The results of the initial image analysis of a proton beam star pattern were not ideal. It was found that the initial assumption that the rotational axis was exactly parallel to

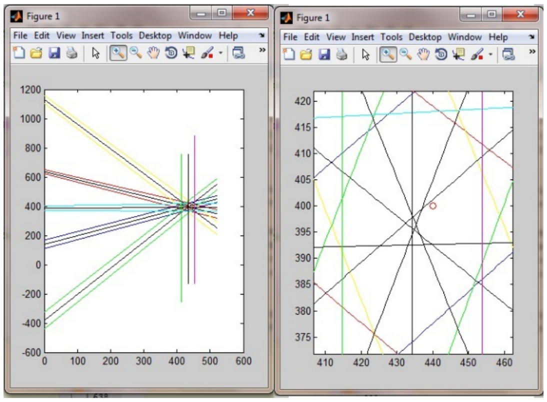

Fig. 8: Beam axes pattern resulting from analysis of Figure 7. The right half of image shows a close-up view of the beam-axes intersection region. 1 pixel = 0.0844 mm

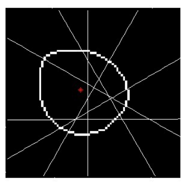

Fig. 9: Results of the six beams image. The largest raw distance from the target to the beam path is 0.211 mm

the z-axis. After the z-axis was determined more accurately by studying the change of a the proton beam position relative to the radiochromic film during a series of discrete rotations, localization accuracy was much improved to better than 0.32 mm. The average target error is significantly better at 0.149 mm $\pm$ 0.058 mm, which demonstrates the high repeatability of this method.

During this research, advanced methods of image analysis of beam patterns visualized with radiochromic films were developed. This included a consistent definition of marker pin holes, the use of a high-resolution algorithm for edge definition, definition of the best practice for film scanning, and methods for taking into account the scanner distortion. Most importantly, a rotational correction program was developed that performs translational corrections after each stage rotation. This allows fast and accurate beam delivery from many consecutive directions. A user-friendly GUI for this program was also developed.

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