Master's Thesis
석사학위논문

New Radiation Robot Design for Reduced Surgery Time and High Accuracy

Geunhan Seo(서 근 한 徐 槿 韓)

Department of Robotics Engineering

로봇공학전공

DGIST

2015

New Radiation Robot Design for Reduced Surgery Time and High Accuracy

Advisor : Professor Pyunghun Chang

Co-advisor : Professor Erkin Gezgin

by

Name

Department of Robotics Engineering

DGIST

A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science. The study was conducted in accordance with Code of Research Ethics[1]

. .2015

Approved by

Professor Pyunghun Chang (Signature)

(Advisor)

Professor Erkin Gezgin (Signature)

(Co-Advisor)

[1] Declaration of Ethical Conduct in Research: I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

New Radiation Robot Design for Reduced Surgery Time and High Accuracy

Geunhan Seo

Accepted in partial fulfillment of the requirements for the degree of Master of Science.

. .2015

Head of Committee	Professor Pyunghun Chang (Signature)
Committee Member	Professor Erkin Gezgin (Signature)
Committee Member	Professor Jaesung Hong (Signature)

MS/RT
201323006

서 근 한. Geunhan Seo. The study of New radiation robot design for reduced surgery time and high accuracy. Department of robotics Engineering. 2015. 31p. Advisors Prof. Pyunghun Chang, Co-Advisors Prof. Erkin Gezgin.

ABSTRACT

Recently, the methods of cancer treatment have been developed. The stereotactic radiosurgery is one of the cancer treatment methods. Gammaknife and the cyberknife system which are the devices of the stereotactic radiosurgery use the radiation beam to remove the tumor in the human body. In this paper, the issues of the stereotactic radiosurgery will be dealt with. The first issue is the surgery time. The surgery time of the stereotactic radiosurgery is 30min to 90min, and the young and old groups of the patients are hard to undergo surgery more than 40min, so the surgery time have to be reduced. The second issue is the beam accuracy. The organs or normal tissues are also affected by radiation beam during the surgery. If they receives radiation energy beam more than they can endure, they lose their own function, so the accurate beam is needed. In this paper, the new radiation robot will be introduced. This new robot has several structural characteristics. : 1) 2 robot manipulators and 2 LINACs, 2) each robot manipulator has 2DOF, 3) LINACs are always targeting the central point, 4) upper and lower robot manipulators are operated independently. By using this new robot which has several structural characteristics, the issues of the radiosurgery will be dealt with.

Keywords: Stereotactic radiosurgery, Gammaknife, Cyberknife, Beam on/off time, Beam accuracy

List of Contents

List of Figures

List of Tables

1. INTRODUCTION

1.1 Radiosurgery

Stereotactic RadioSurgery (SRS) is one of the cancer treatment methods. In 1951, Swedish neurosurgeon Lars Leksell of the Karolinska Institute Stockholm proposed Stereotactic RadioSurgery (SRS).[1] SRS is a non-invasive technique to eliminate the tumors which are located in the center of semicircular arch by using external radiation beams. Figure 1 represents the treatment beam geometry of cyberknife system. Cyberknife is one of the SRS devices, and it will be introduced in chapter 1.1.2.[2] It can be used to remove the tumors in inaccessible or unsuitable for open surgery.[1, 3] In the beginning, SRS was used only the intracranial tumors.[4] Nowadays, SRS is used for the tumors in the whole body.[5]

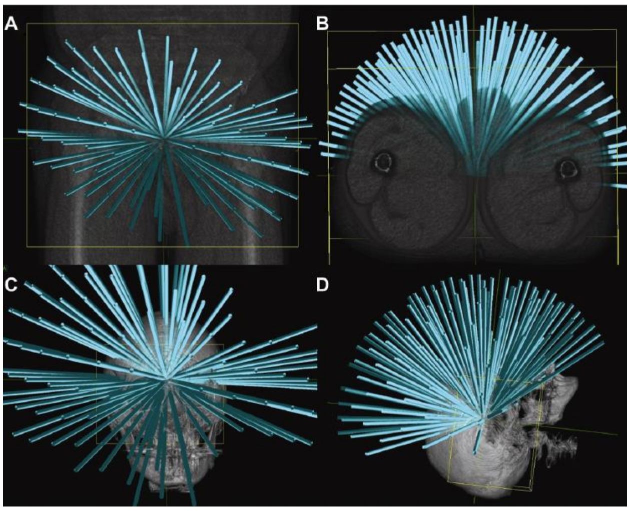

Figure 1 Treatment beam geometry of cyberknife system

1.1.1 Gammaknife

In 1968, the first gammaknife was installed at the Karolinska Institute. Figure 2 represents a picture of the gammaknife unit.[3, 6] This device had 179 Cobalt60 sources, and it was used to treat brain tumors and intracranial arteriovenous malformations (AVM).[7, 8] Each Cobalt60 source was located in hemisphere shape device and pointed toward a point.[6] After 1980s, gamma-knife which has 201 Cobalt60 sources is used to remove the intracranial tumors.[9] It can use multiple beams simultaneously to treat the cancer.[9] Nowadays, gammaknife is used globally, but it has some weaknesses. Gammaknife is used for only intracranial tumors, and it has a frame to fix a head of patient.[3, 10] Although gammaknife has these weaknesses, it is used widely, because it has high accuracy for intracranial tumors.

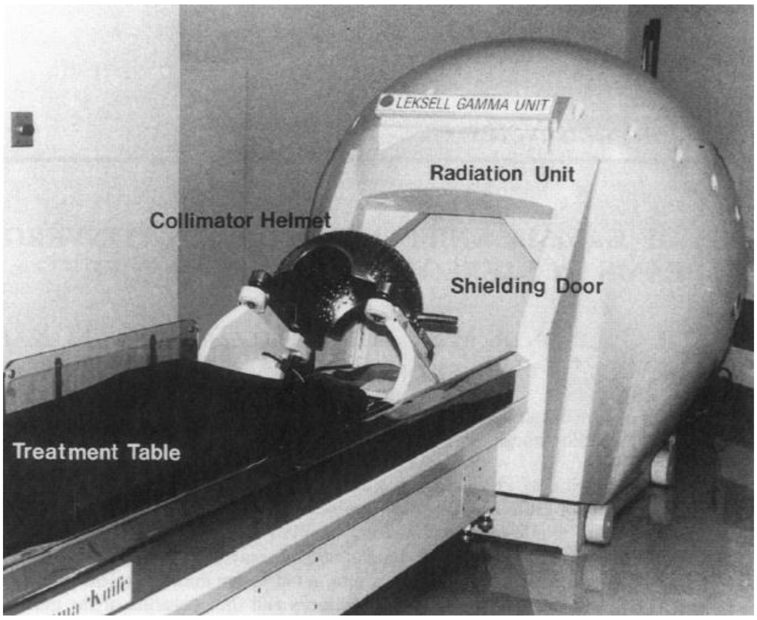

Figure 2 The first gammaknife unit.

1.1.2 Cyberknife

The cyberknife system is also one of the radiosurgery devices. In 1994, it is developed by Accuracy Incorporated. The cyberknife has no frame, and it has conventional linear accelerator (LINAC) at the head of robot manipulator. It uses a single high radiation energy beam by using 1 LINAC.[11] Figure 3 represent the cyberknife VSI system which is most recent version.[2] The cyberknife uses 1,320 beam paths to remove the whole body tumors.[12] These beams have high precision, because cyberknife system uses the X-ray image guidance.[13] In 2001, the cyberknife system received approval by FDA “anywhere in the body where radiation treatment is indicated”.[14] This device is frameless system, so it overcomes the weaknesses of devices which has frame.[9] Nowadays, it is used globally to treat for whole body cancer.[5, 15]

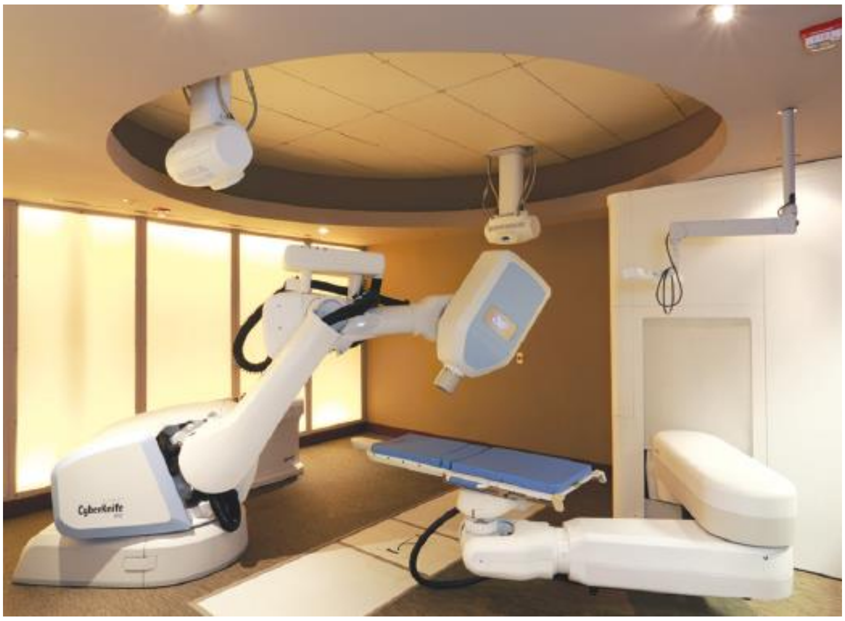

Figure 3 The cyberknife VSI system

1.2 Purpose of research

In chapter 1.1, stereotactic radiosurgery and its devices were introduced. These devices are very suitable to remove the tumors in human body.[5] However, these devices are not perfect. In case of gammaknife, it can only treat brain tumors and intracranial arteriovenous malformations (AVM), and it has a frame to fix the patient head.[3, 10] These weaknesses can be overcome by using another device like cyberknife.[13] Like this, there are several issues in stereotactic radiosurgery. In this research, two issues of radiosurgery are dealt with.

To reduce the total surgery time is one of the issues in the stereotactic radiosurgery. The total surgery time of stereotactic radiosurgery devices is 30min to 90min for one surgery.[16] The devices of radiosurgery use the beam nodes which are planned in treatment planning. The initial patient position is reference to plan the beam nodes, and if patient position is changed, the beam paths are also changed. Because of this reason, the patients have to maintain their initial position. However a several subgroups of patients like pediatric or elderly patients have difficulties related with stringent immobilization and long surgery time more than 40min.[17] In cyberknife system, the LINAC at the head of robot manipulator had developed to reduce the total surgery time.[2]

The high accurate beam is also important issue in the stereotactic radiosurgery. The surrounding normal tissues or important organs are influenced by radiation beam when the stereotactic radiosurgery devices irradiate the beam to the tumors.[16] The important organs and surrounding normal tissues are sensitive. If they are affected by high radiation beam energy, they lose their own functions. Therefore the radiation beam accuracy is important in radiosurgery. Gammaknife has high beam accuracy because it use the frame to fix the patients head.[3] Cyberknife system has used the accurate 6DOF robot manipulator and couch, and used x-ray image processing so it obtains the high accurate beam.[2]

In this research, to reduce the total surgery time and high accurate beam are dealt with. The new radiation robot is proposed to deal with these issues. The new radiation robot has two LINACs at the end of 2DOF radiation robot manipulators and each LINAC could operate independently, and is indicating the one point in any posture. The issues are dealt with by using these structural characteristics of new radiation robot.

This paper is divided by four chapters. In the chapter 1, introduction part, radiosurgery and purpose of this research are introduced. In the chapter 2, new radiation robot part, structural characteristics of new radiation robot and mathematical equations of new radiation robot will be introduced. In the chapter 3, experiment and result part, the simulations for reduced surgery time and high accurate beam will be introduced. In the chapter 4, discussion and conclusion part, summary and future directions will be introduced.

2. NEW RADIATION ROBOT

In this chapter, new radiation robot will be introduced in detail. To reduce the total surgery time of stereotactic radiosurgery and irradiate the accurate beam are the purpose of this research. To deal with these issues, in chapter 2, the structural characteristics of new radiation robot will be introduced firstly, and mathematical equations of new radiation robot will be introduced.

2.1 Structural characteristics of new radiation robot

New radiation robot design has several structural characteristics: 1) New radiation robot consists of two robot manipulators, upper and lower robots, and each robot manipulator has linear accelerator (LINAC). The blue ellipses in figure 4 represent each 2DOF robot manipulator, and end of each robot manipulator (red box) is LINAC model.

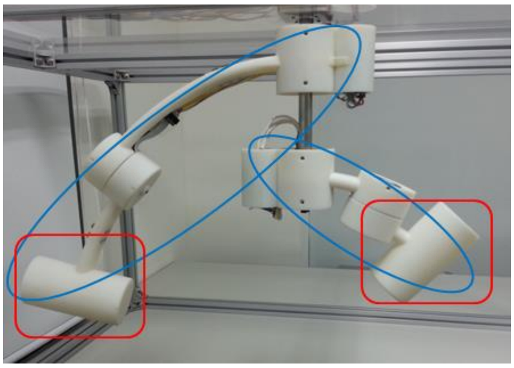

Figure 4 The prototype of new radiation robot (2 robot manipulators and 2 LINACs)

2) Each robot manipulator has two degree of freedom. (Figure 5)

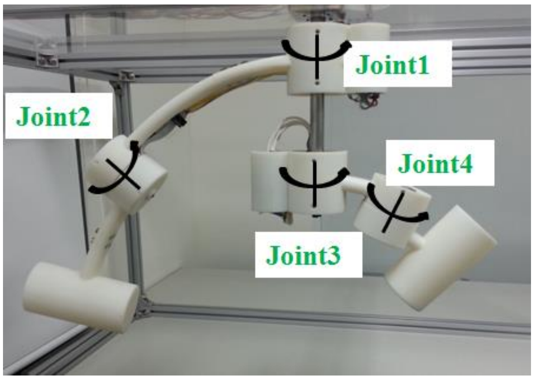

Figure 5 The prototype of new radiation robot (Each robot manipulator has two DOF)

3) Each LINAC is always indicating the central point in any posture. (Figure 6(a))

4) There is no collision between upper robot and lower robot, in other words, each robot is operated independently. (Figure 6(b))

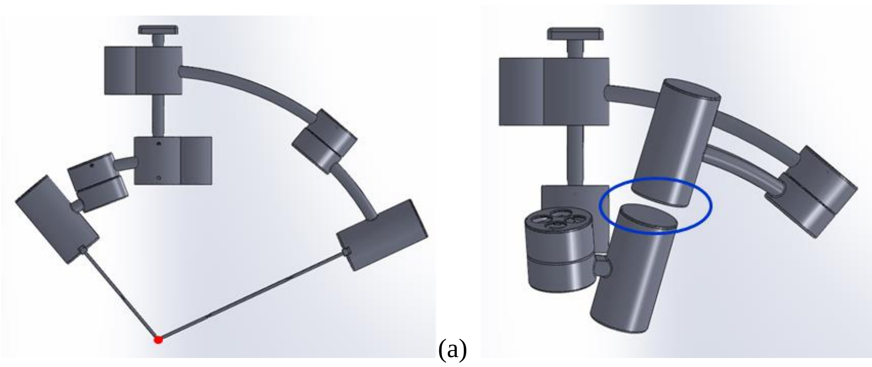
(a) (b)

Figure 6 The 3D cad model of new radiation robot

To overcome the issues of radiosurgery, the new radiation robot was designed.

2.2 Mathematical equations of new radiation robot

In this chapter, the mathematical equations related with the new radiation robot will be introduced. Figure 7 represents the kinematics representation of new radiation robot. The distance between 0-axis and iso-point is 2,500mm. The angle between joint 1 and joint2 is 40 degree, and the angle between joint 2 and upper LINAC model is 25 degree. The angle between joint 3 and joint 4 is 21 degree, and the angle between joint 4 and lower LINAC is 19 degree. From 0-axis to 3-axis and world axis are determined in figure 8.

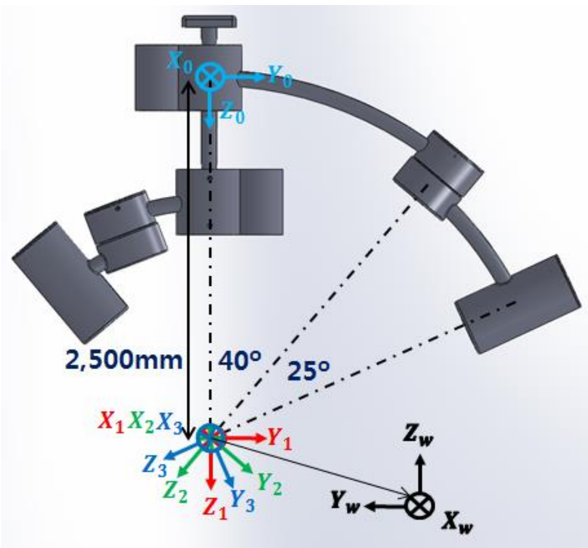

Figure 7 The kinematics representation of new radiation robot

Each axis is labeled with respect to the Denavit-Hatenberg convention. The Denavit-Hatenberg parameters of the upper robot manipulator of the new radiation robot are in Table 1.

Table 1 The Denavit-Hatenberg parameters of the upper robot manipulator

Joint i	α_i	a_i	d_i	θ_i
1	0	0	2.5	θ_1
2	40°	0	0	θ_2
3	25°	0	0	0

Here are the homogeneous transfer functions of upper robot manipulator.

$$
{}^{w}T_0 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 2.5 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad {}^{0}T_1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 2.5 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{1}T_2 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & 0 \\ \sin\theta_2 * \cos(40°) & \cos\theta_2 * \cos(40°) & -\sin(40°) & 0 \\ \sin\theta_2 * \sin(40°) & \cos\theta_2 * \sin(40°) & \cos(40°) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{2}T_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(25°) & -\sin(25°) & 0 \\ 0 & \sin(25°) & \cos(25°) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad {}^{w}T_3 = {}^{w}T_0\,{}^{0}T_1\,{}^{1}T_2\,{}^{2}T_3
$$

The homogeneous transfer function between world-axis and 3-axis (${}^{w}T_3$) is here. $u_x, u_y, u_z, v_x, v_y, v_z, w_x,$ w_y, w_z, p_x, p_y, p_z represent each term of ${}^{w}T_3$.

$$
{}^{w}T_3 = \begin{bmatrix} u_x & v_x & w_x & p_x \\ u_y & v_y & w_y & p_y \\ u_z & v_z & w_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$u_x = ct1*ct2 - c40*st1*st2,\ \ u_y = -ct2*st1 - c40*ct1*st2,\ \ u_z = -s40*st2$$

$$v_x = s25*s40*st1 - c25*(ct1*st2 + c40*ct2*st1)$$

$$v_y = c25*(st1*st2 - c40*ct1*ct2) + ct1*s25*s40,\ \ v_z = ct2*s25*s40 - c25*c40$$

$$w_x = s25*(ct1*st2 + c40*ct2*st1) + c25*s40*st1$$

$$w_y = c25*ct1*s40 - s25*(st1*st2 - c40*ct1*ct2)$$

$$w_z = ct2*s25*s40 - c25*c40,\ \ p_x = 0,\ \ p_y = 0,\ \ p_z = 0$$

The workspace of the new radiation robot is in figure 8. Figure 8 represents the workspace of upper LINAC model end tip of 3d printer prototype, and figure 9 represents the workspace of lower LINAC model end tip.

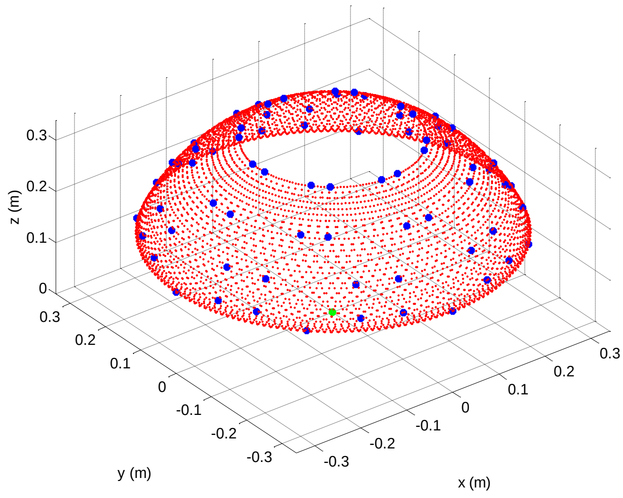

Figure 8 The workspace of upper LINAC model end tip of 3d printer prototype

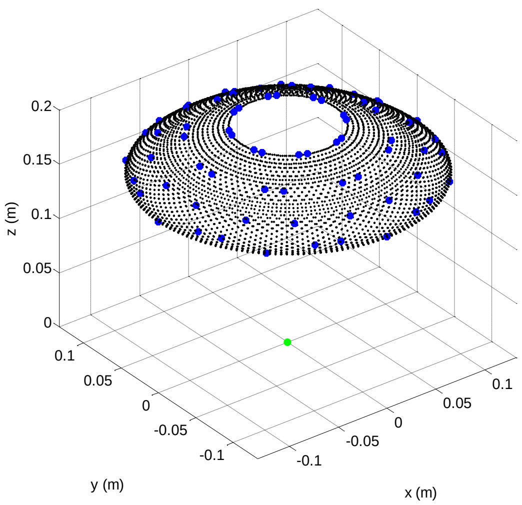

Figure 9 The workspace of lower LINAC model end tip of 3d printer prototype

In chapter 2, the structural characteristics and the mathematical equations of new radiation robot are introduced in detail. The homogeneous transfer functions are written in this chapter, and these functions are used in chapter3 to check the beam accuracy. The structural characteristics of the new radiation robot and the equations will be used to simulate for reduced surgery time and high accurate beam.

3. EXPERIMENT AND RESULT

In chapter 2, structural characteristics and mathematical equations of the new radiation robot were introduced. Throughout this chapter, the simulations related with surgery time and beam accuracy will be explained, and show that the new radiation robot can overcome the issues of the stereotactic radiosurgery.

3.1 Reduced surgery time

In the stereotactic radiosurgery, reducing the total surgery time is an important issue. The pediatric or elderly patients groups could face difficulties related with stringent immobilization and long surgery time.[17] If the patients feel hard to maintain the initial position, the tumor position is changed. In that case, the surrounding normal tissues and important organs are affected, so the changed tumor position has to be in the initial position, and it needs time to correct the position.[16] Because of these reasons, to reduce the surgery time is important issue. In this chapter, to reduce the surgery time will be explained by using the new radiation robot.

In cyberknife system which is one of the stereotactic radiosurgery devices, the total surgery time for one surgery is 30min to 90min.[16] This device uses one LINAC, and the total surgery time is divided into two parts: 1)Beam on time, 2) Beam off time. When the LINAC irradiates the beam to the tumor in human body, it is called beam on time. When the LINAC moves planned point A to point B, the LINAC can’t irradiate a radiation beam, and it is called beam off time. Image processing time and control time are belong to beam off time. The two-thirds of the total surgery time is beam on time, and one-thirds is beam off time.[16] In the cyberknife system, it uses only one LINAC, so there is wasted time like robot manipulator moving time. In this research, the new radiation robot uses two LINACs. Therefore it could reduce the robot manipulator moving time.

In this chapter, there are simulations to deal with surgery time by using the new radiation robot. Here are the simulation assumptions.

1) There are two cases for simulation. (Figure 10)

Case 1 : use 1 LINAC (upper LINAC)

Case 2 : use 2 LINAC (upper LINAC and lower LINAC)

2) Use the same LINACs (LINAC spec: 600MU/min = 10MU/sec)

3) There is one tumor, and it receives 600MU. (Figure 10)

4) There are 10 beam paths.

5) Beam on time: 60sec, beam off time: 35sec

6) Measure the total surgery time (Beam on time + beam off time)

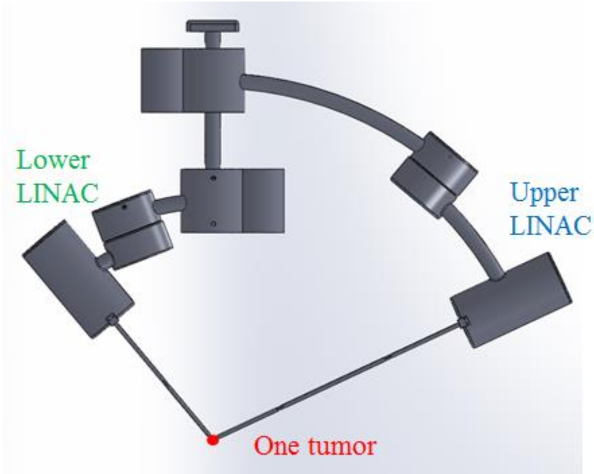

Figure 10 The 3d cad model of the new radiation robot

3.1.1 Case 1: use 1 LINAC (Upper LINAC)

In this case, there is one LINAC. The red circle in the figure 10 is the tumor which received 600MU. The beam paths are 10, and LINAC can irradiate the beam 10MU/sec. The tumor receive 600MU by 60sec beam on time, and robot manipulator moving time plus image processing time equal 35sec. These assumptions are ready to simulate for surgery time.

At first, upper LINAC move to 1st beam path by using 2sec of beam off time, and irradiate the beam to the tumor during 6sec beam on time. Next, it moves to second beam path by using 3sec of beam off time, and irradiate the beam during 6sec beam on time. These are repeated until the tumor receives 600MU. Figure 11 represent the case 1. In the figure 11, red blocks are beam off time and blue blocks are beam on time.

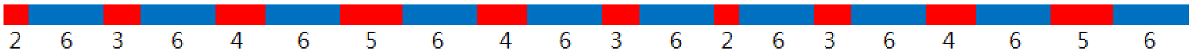

Figure 11 Case 1: use 1 LINAC (upper LINAC)

In the case 1, the total surgery time equals to beam on time plus beam off time. Because there is 1 LINAC, all time is cumulated, so the total surgery time (95sec) is beam on time (60sec) plus beam off time (35sec).

3.1.2 Case 2: use 2 LINACs (Upper LINAC and lower LINAC)

In this case, there are two LINACs, and other assumptions are same related with case 1.

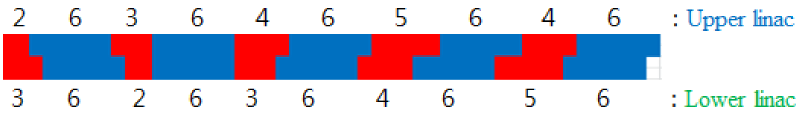

Figure 12 Case 2: use 2 LINACs (Upper LINAC and lower LINAC)

Figure 12 represent the case 2. Red blocks are beam off time, and blue block are beam on time. Upper line is for upper LINAC, and lower line is for lower LINAC. In the upper LINAC, the beam off time is 18sec, and the beam on time is 30sec, so the total time of upper LINAC is 48sec. In the lower LINAC, the beam off time is 17sec, and the beam on time is 30sec, so the total time of lower LINAC is 47sec. Each surgery time is 48sec, and 47 sec. However, the new radiation robot uses two LINACs independently, so the total surgery time is only 48sec.

There are two cases simulation. Case 1 uses one LINAC, so the total surgery time equal to beam on time and beam off time, in other words, it needs beam on time and beam off time all. Case 2 uses two LINACs, so the beam on time and beam off time is divided into two parts, that is, upper LINAC and lower LINAC. Because each LINAC operates independently, the total surgery time is only 48sec, that is, upper LINAC's surgery time. By using two LINACs independently instead of one LINAC, the surgery time is reduced.

3.2 High accuracy

In radiation therapy, accuracy of beam is also important issue. When the LINAC irradiates the radiation beam to the tumor in human body, tumors and surrounding normal tissues are influenced by radiation beam. The surrounding normal tissues and important organs are very sensitive, so it can't function properly if radiation beam is irradiated to these tissues.[18] In this chapter, simulations show that the new radiation robot has high accurate beam.

The new radiation robot has two robot manipulators, and each robot manipulator has just two degree of freedom. The LINACs on the end tip of robot manipulators are always pointing the central point in any posture. These features will be used to show that the new radiation robot is accurate.

In this chapter, the new robot's accuracy will be compared with cyberknife. In this comparison, upper robot of the new robot will be used. Upper robot of the new robot has 2DOF, and it is always indicating the central point. For the comparison, DH parameters and homogeneous transfer functions of the new radiation robot and cyberknife is needed. In chapter 2, there are DH parameters and homogeneous transfer functions of new radiation robot. For the cyberknife's robot manipulator is here. Figure 13 represents the kinematic representation of cyberknife's robot manipulator (KUKA kr240-2). The DH parameters of robot manipulator of cyberknife are in table 2.

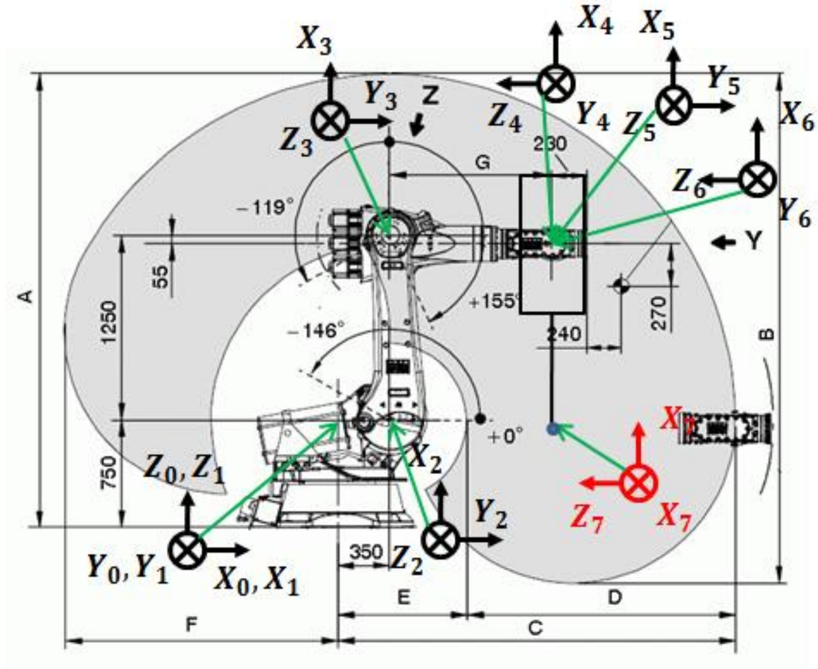

Figure 13 The kinematic representation of cyberknife's robot manipulator

Table 2 DH parameter of cyberknife robot manipulator

Joint i	α_i	a_i	d_i	θ_i
1	0	0	0	θ_1
2	-90	350	0	θ_{2-90}
3	0	1250	0	θ_3
4	90	0	-1100	θ_4
5	-90	0	0	θ_5
6	90	0	0	θ_6

The homogeneous transfer functions of the robot manipulator of cyberknife are here.

$$ {}^{0}T_{1} = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 2.5 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad {}^{1}T_{2} = \begin{bmatrix} \sin\theta_2 & \cos\theta_2 & 0 & 0.35 \\ 0 & 0 & 1 & 0 \\ \cos\theta_2 & -\sin\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{2}T_{3} = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & 1.25 \\ \sin\theta_3 & \cos\theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad {}^{3}T_{4} = \begin{bmatrix} \cos\theta_4 & -\sin\theta_4 & 0 & 0 \\ 0 & 0 & -1 & 1.1 \\ \sin\theta_4 & \cos\theta_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{4}T_{5} = \begin{bmatrix} \cos\theta_5 & -\sin\theta_5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\theta_5 & -\cos\theta_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad {}^{5}T_{6} = \begin{bmatrix} \cos\theta_6 & -\sin\theta_6 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ \sin\theta_6 & \cos\theta_6 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, $$

$$ {}^{6}T_{7} = \begin{bmatrix} 1 & 0 & 0 & -1.28 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad {}^{0}T_{7} = {}^{0}T_{1}{}^{1}T_{2}{}^{2}T_{3}{}^{3}T_{4}{}^{4}T_{5}{}^{5}T_{6}{}^{6}T_{7} $$

$$ {}^{0}T_{7} = \begin{bmatrix} H\_11 & H\_12 & H\_13 & H\_14 \\ H\_21 & H\_22 & H\_23 & H\_24 \\ H\_31 & H\_32 & H\_33 & H\_34 \\ H\_41 & H\_42 & H\_43 & H\_44 \end{bmatrix} $$

H_11 to H_44 are represented the each terms of ${}^{0}T_{7}$. ${}^{0}T_{7}$ is written in appendices.

Here are the assumptions of simulations for high accuracy.

1) There are two cases

Case 1: Cyberknife KUKA kr240-2 (6DOF robot manipulator)

Case 2: The new radiation robot (2DOF robot manipulator)

2) Cyberknife's motors and the new radiation robot's motors are same. (The error of each motor is 0.2 degree)

3) Each case has two conditions

Condition 1 : Each motor has no error.

Condition 2 : Each motor has 0.2 degree error.

4) Check the error between condition 1 and condition 2.

3.2.1 Case 1: Cyberknife KUKA kr240-2 (6DOF)

In the cyberknife system, ${}^{0}R_{7}$ is used for simulation. ${}^{0}R_{7}$ is 0 to 7 rotation matrix and it represents condition 1. ${}^{0}R_{7*}$ is 0 to 7' rotation matrix, and it represents condition 2. ${}^{7}R_{7*}$ is 7 to 7' rotation matrix, and it represents orientation between condition 1 and condition 2. If use the transform equation, the orientation between condition 1 and condition 2. If ${}^{0}R_{7}$ is invertible, ${}^{7}R_{7*}$ could be calculated. See the lower equations.

$${}^{0}R_{7}{}^{7}R_{7*} = {}^{0}R_{7*}, \quad {}^{7}R_{7*} = ({}^{0}R_{7})^{-1} * {}^{0}R_{7*}$$

$$ {}^{0}R_{7} = \begin{pmatrix} 0 & 0 & -1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \quad {}^{0}R_{7*} = \begin{pmatrix} 0.0104 & -0.0036 & -0.9999 \\ 0.007 & 1 & -0.0035 \\ 0.9999 & -0.007 & 0.0105 \end{pmatrix} $$

$$ {}^{7}R_{7*} = ({}^{0}R_{7})^{-1} * {}^{0}R_{7*} = \begin{pmatrix} 0.9999 & -0.007 & 0. \\ 0.007 & 1 & -0. \\ -0.0104 & 0.0036 & 0. \end{pmatrix} $$

If substitute ${}^{7}R_{7*}$ to roll, pitch, yaw angle equation (figure 14)[19], we can get the orientation between condition 1 and condition 2.

Roll, pitch, yaw angle equation

$$ {}^{A}_{B}\boldsymbol{R}_{xyz}(\gamma, \beta, \alpha) = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} $$

$$ \beta = Atan2(-r_{31}, \sqrt{r^{2}{}_{11} + r^{2}{}_{21}}) $$
$$ \alpha = Atan2(r_{21}/cos\beta,\ r_{11}/cos\beta) $$
$$ \gamma = Atan2(r_{32}/cos\beta,\ r_{33}/cos\beta) $$

Figure 14 Roll, pitch, yaw angle equation

γ = 0.2063° (x-axis), β = 0.5959° (y-axis), α = 0.4011° (z-axis)

These angles represent the orientation between condition 1 and condition 2 of Cyberknife robot manipulator.

3.2.2 Case 2: The new radiation robot (2DOF)

In the new radiation robot system, ${}^{w}R_{3}$ is used for simulation. ${}^{w}R_{3}$ is world to 3 rotation matrix, and it represents condition 1. ${}^{w}R_{3*}$ is w to 3' rotation matrix, and it represents condition 2. ${}^{3}R_{3*}$ is 3 to 3' rotation matrix, and it represents orientation between condition 1 and condition 2. If use the transform equation, the orientation between condition 1 and condition 2. If ${}^{w}R_{3}$ is invertible, ${}^{3}R_{3*}$ could be calculated. See the lower equations.

$${}^{w}R_{3}\,{}^{3}R_{3*} = {}^{w}R_{3*}, \quad {}^{3}R_{3*} = ({}^{w}R_{3})^{-1} * {}^{w}R_{3*}$$

$${}^{w}R_{3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -0.4226 & 0.9063 \\ 0 & -0.9063 & -0.4226 \end{pmatrix}, \quad {}^{w}R_{3*} = \begin{pmatrix} 1 & -0.0046 & 0.0046 \\ -0.0062 & -0.4226 & 0.9063 \\ -0.0022 & -0.9063 & -0.4226 \end{pmatrix}$$

$${}^{3}R_{3*} = ({}^{w}R_{3})^{-1} * R_{3*} = \begin{pmatrix} 1 & -0.0046 & 0.0 \\ 0.0046 & 1 & \\ -0.0047 & 0 & 1 \end{pmatrix}$$

The orientation between condition 1 and condition 2 is obtained by using roll, pitch, yaw angle equation (figure 14).

γ = 0° (x-axis), β = 0.2687° (y-axis), α = 0.2644° (z-axis)

γ = 0.2063°, β = 0.5959°, α = 0.4011° is the orientation of cyberknife.

γ = 0°, β = 0.2687°, α = 0.2644° is the orientation of the new radiation robot.

The new radiation robot is more accurate than cyberknife system, because it uses just 2DOF robot manipulator and it is always indicating the target point.

4. DISCUSSION AND CONCLUSION

4.1 Discussion

There were two cases to check the surgery time. First case uses 1 LINAC, and second case uses 2LINACs. By using the two LINACs, the surgery time is reduced. In this simulation, the new radiation robot is used, and the assumptions are just for small radiation energy. In the next research, the assumptions will be chosen for one surgery time.

There were also two cases to check the beam accuracy. The robot manipulators of the cyberknife system (KUKA kr240-2) and the new radiation robot are used. In this paper, the tumor is fixed, and the robot manipulators were only considered. However, to check the beam accuracy properly, the treatment couch is also needed, so in the next research, it will be considered.

In this paper, the issues of stereotactic radiosurgery were dealt with, and the new radiation robot was introduced. The two LINACs of the new radiation robot are operated independently, so the total surgery time is reduced. The beam of the new radiation robot has accurate, because it uses 2DOF robot manipulators and is always indicating the central point. The new radiation robot design has more strong points. It could use the simple equation to control, and it uses just 2DOF robot manipulators, therefore it is cheaper than more DOF robot manipulator devices. In the next research, tumors which could move small distance will be considered. In other words, the new radiation robot will have 3DOF robot manipulator to compensate the tumor motion like respiratory motion.

4.2 Conclusion

In this research, the new radiation robot design was introduced. The new radiation robot has several structural characteristics. 1) The proposed robot design has two robot manipulators, and each robot manipulator has LINAC. 2) Each robot manipulator has 2 degree of freedom. 3) Each LINAC is always indicating the iso-point in any posture. 4) Upper robot manipulator and lower robot manipulator are operated independently, and there is no collision between them. These structural characteristics are used to overcome the issues of stereotactic radiosurgery.

The first issue of stereotactic radiosurgery is surgery time. The several groups of patients like pediatric or elderly patients may face difficulties to endure the long surgery time.[17] The new radiation robot has two LINACs, and each LINAC could operate independently. By using these structural characteristics, the total surgery time could be reduced. In this paper, there are two cases for reduced surgery time. First case uses 1 LINAC, so the surgery time is not decreased. The total surgery time (95sec) equals to beam on time (60sec) plus beam off time (35sec). Second case uses 2 LINACs independently, so the surgery time is decreased. The total surgery time (48sec) equals to beam on time (30sec) plus beam off time (beam off time). By using two LINACs, the total surgery time is decreased by about half.

The beam accuracy is also important issue of stereotactic radiosurgery. If the important organs or normal tissues surrounding tumors receive high radiation energy beam, they lose their own functions.[18] The new radiation robot has 2DOF robot manipulators, and the LINACs are always indicating the central point. By using these structural characteristics of the new radiation robot, the beam could have high accuracy. The cyberknife system is accurate, and it is used widely to treat tumors.[5, 15] In this paper, to check the beam accuracy of the new radiation robot, cyberknife robot system is used. The main assumption of this simulation is motor error. The all motors of robot manipulators have 0.2 degree error. The orientations are here.

The orientation of cyberknife: $\gamma = 0.2063^\circ$, $\beta = 0.5959^\circ$, $\alpha = 0.4011^\circ$

The orientation of the new robot: $\gamma = 0^\circ$, $\beta = 0.2687^\circ$, $\alpha = 0.2644^\circ$

The simulation result show that the beam of the new radiation robot is more accurate than cyberknife robot manipulator. The robot manipulator of the new radiation robot uses just 2 DOF, and the beams which are irradiated at LINACs are always pointing the central point. Because of these structural characteristics, the beam of the new radiation robot has high accuracy.

APPENDICES

$$ {}^{0}T_{7} = \begin{bmatrix} H\_11 & H\_12 & H\_13 & H\_14 \\ H\_21 & H\_22 & H\_23 & H\_24 \\ H\_31 & H\_32 & H\_33 & H\_34 \\ H\_41 & H\_42 & H\_43 & H\_44 \end{bmatrix} $$

H_11=ct6*(st5*(ct1*ct2*ct3 - ct1*st2*st3) - ct5*(st1*st4 - ct4*(ct1*ct2*st3 + ct1*ct3*st2))) - st6*(ct4*st1 + st4*(ct1*ct2*st3 + ct1*ct3*st2))

H_12=- st6*(st5*(ct1*ct2*ct3 - ct1*st2*st3) - ct5*(st1*st4 - ct4*(ct1*ct2*st3 + ct1*ct3*st2))) - ct6*(ct4*st1 + st4*(ct1*ct2*st3 + ct1*ct3*st2))

H_13= - ct5*(ct1*ct2*ct3 - ct1*st2*st3) - st5*(st1*st4 - ct4*(ct1*ct2*st3 + ct1*ct3*st2))

H_14=(7*ct1)/20 + (5*ct1*st2)/4 - (32*ct6*(st5*(ct1*ct2*ct3 - ct1*st2*st3) - ct5*(st1*st4 - ct4*(ct1*ct2*st3 + ct1*ct3*st2))))/25 + (32*st6*(ct4*st1 + st4*(ct1*ct2*st3 + ct1*ct3*st2)))/25 + (11*ct1*ct2*ct3)/10 - (11*ct1*st2*st3)/10

H_21= ct6*(st5*(ct2*ct3*st1 - st1*st2*st3) + ct5*(ct1*st4 + ct4*(ct2*st1*st3 + ct3*st1*st2))) + st6*(ct1*ct4 - st4*(ct2*st1*st3 + ct3*st1*st2))

H_22= ct6*(ct1*ct4 - st4*(ct2*st1*st3 + ct3*st1*st2)) - st6*(st5*(ct2*ct3*st1 - st1*st2*st3) + ct5*(ct1*st4 + ct4*(ct2*st1*st3 + ct3*st1*st2)))

H_23=st5*(ct1*st4 + ct4*(ct2*st1*st3 + ct3*st1*st2)) - ct5*(ct2*ct3*st1 - st1*st2*st3)

H_24=(7*st1)/20 + (5*st1*st2)/4 - (32*ct6*(st5*(ct2*ct3*st1 - st1*st2*st3) + ct5*(ct1*st4 + ct4*(ct2*st1*st3 + ct3*st1*st2))))/25 - (32*st6*(ct1*ct4 - st4*(ct2*st1*st3 + ct3*st1*st2)))/25 + (11*ct2*ct3*st1)/10 - (11*st1*st2*st3)/10

H_31=- ct6*(st5*(ct2*st3 + ct3*st2) - ct4*ct5*(ct2*ct3 - st2*st3)) - st4*st6*(ct2*ct3 - st2*st3)

H_32= st6*(st5*(ct2*st3 + ct3*st2) - ct4*ct5*(ct2*ct3 - st2*st3)) - ct6*st4*(ct2*ct3 - st2*st3)

H_33=ct5*(ct2*st3 + ct3*st2) + ct4*st5*(ct2*ct3 - st2*st3)

H_34=(5*ct2)/4 - (11*ct2*st3)/10 - (11*ct3*st2)/10 + (32*ct6*(st5*(ct2*st3 + ct3*st2) - ct4*ct5*(ct2*ct3 - st2*st3)))/25 + (32*st4*st6*(ct2*ct3 - st2*st3))/25

H_41=0

H_42=0

H_43=0

REFERENCES

[1] L. Leksell, "The stereotaxic method and radiosurgery of the brain," *Acta Chir. Scand.*, vol. 102, pp. 316-319, 1951.

[2] W. Kilby, J. Dooley, G. Kuduvalli, S. Sayeh, and C. Maurer, "The CyberKnife® robotic radiosurgery system in 2010," *Technology in cancer research & treatment*, vol. 9, pp. 433-452, 2010.

[3] L. Leksell, "Stereotactic radiosurgery," *Journal of Neurology, Neurosurgery & Psychiatry*, vol. 46, pp. 797-803, 1983.

[4] S. C. Pannullo, A. G. Wernicke, and C. Yama, *Stereotactic Radiosurgery for Brain Tumors*: INTECH Open Access Publisher, 2011.

[5] È. Coste-Manière, D. Olender, W. Kilby, and R. Schulz, "Robotic whole body stereotactic radiosurgery: clinical advantages of the CyberKnife® integrated system," *The International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 1, pp. 28-39, 2005.

[6] A. Wu, G. Lindner, A. Maitz, A. Kalend, L. Lunsford, J. Flickinger, *et al.*, "Physics of gamma knife approach on convergent beams in stereotactic radiosurgery," *International Journal of Radiation Oncology* Biology* Physics*, vol. 18, pp. 941-949, 1990.

[7] E. M. Housepian, "Stereotaxis and Radiosurgery: An Operative System," *Archives of Neurology*, vol. 25, pp. 576-576, 1971.

[8] B. Larsson, K. Lidén, and B. Sarby, "Irradiation of small structures through the intact skull," *Acta radiologica: therapy, physics, biology*, vol. 13, pp. 512-534, 1974.

[9] S. C. Hoffelt, "Gamma knife vs. cyberKnife," *Oncology Issues*, vol. 21, pp. 18-20, 2006.

[10] L. Lunsford and M. Linskey, "Stereotactic radiosurgery in the treatment of patients with acoustic tumors," *Otolaryngologic Clinics of North America*, vol. 25, pp. 471-491, 1992.

[11] J. R. Adler Jr, S. Chang, M. Murphy, J. Doty, P. Geis, and S. Hancock, "The Cyberknife: a frameless robotic system for radiosurgery," *Stereotactic and functional neurosurgery*, vol. 69, pp. 124-128, 1997.

[12] R. I. Whyte, R. Crownover, M. J. Murphy, D. P. Martin, T. W. Rice, M. M. DeCamp, *et al.*, "Stereotactic radiosurgery for lung tumors: preliminary report of a phase I trial," *The Annals of thoracic surgery*, vol. 75, pp. 1097-1101, 2003.

[13] I. Gibbs, "Frameless image-guided intracranial and extracranial radiosurgery using the Cyberknife™ robotic system," *Cancer/Radiotherapie*, vol. 10, pp. 283-287, 2006.

[14] I. C. Gibbs, S. D. Chang, and J. R. Adler Jr, "Cyber-Knife radiosurgery experience at Stanford university," *Robotic Radiosurgery,* vol. 1, pp. 33-35, 2005.

[15] P. Gerszten and W. Welch, "Cyberknife radiosurgery for metastatic spine tumors," *Neurosurgery clinics of North America,* vol. 15, p. 491, 2004.

[16] W. Brown, X. Wu, J. Fowler, S. Garcia, F. Fayad, B. Amendola*, et al.*, "Lung Metastases Treated by CyberKnife (R) Image-Guided Robotic Stereotactic Radiosurgery at 41 Months," *Southern medical journal,* vol. 101, pp. 376-382, 2008.

[17] B. Joseph, S. S. Supe, and A. Ramachandra, "Cyberknife: A double edged sword?," *Reports of Practical Oncology & Radiotherapy,* vol. 15, pp. 93-97, 2010.

[18] C. R. King, J. Lehmann, J. R. Adler, and J. Hai, "CyberKnife radiotherapy for localized prostate cancer: rationale and technical feasibility," *Technology in cancer research & treatment,* vol. 2, pp. 25-29, 2003.

[19] A. J. Critchlow, *Introduction to robotics*: Macmillan New York, 1985.

요 약 문

짧은 수술시간과 높은 정확도를 위한 새로운 방사선 로봇 디자인

본 연구에서는 cyberknife 와 같이 선형가속기를 이용하는 새로운 방사선 로봇을 디자인하여 제안하였다. 최근 암 환자의 수가 늘어남에 따라 개복수술과 항암제뿐만 아니라 방사선을 이용해서 암을 치료하는 방법에 대해 연구가 많이 진행되고 있다. 방사선을 이용해서 암을 치료하는 방식 중 방사선 수술(Radiosurgery)에 관해서 다루었다. 방사선 수술을 연구하는데 있어서 몇 가지 issue 들이 있다. 본 연구에서는 두 가지 issue 에 대해 다룰 것인데, 하나는 수술시간을 단축시키는 것과 다른 하나는 beam 의 정확도이다. 수술시간이 issue 가 되는 이유는 방사선 수술은 한 자세를 유지하면서 받아야 되는데, 수술시간이 길어지면 나이가 어린 환자나 노인 환자들이 수술을 받을 때 한 자세를 유지하는데 부담이 되며 몸이 움직여질 수가 있기 때문이다. 그리고 정확도가 중요한 이유는 다음과 같다. 몸 속의 tumor 를 제거하기 위해 beam 이 조사될 때 tumor 주변의 일반 세포나 민감한 중요 기관에도 beam 이 영향을 끼치게 되는데 견딜 수 있는 양보다 많은 방사선 에너지가 영향을 주면 기능을 잃을 수도 있다. 이 논문에서는 위와 같은 issue 들을 위해 다음과 같은 구조적인 특징을 가진 새로운 로봇을 제안한다. 2 개의 linac 을 이용하며 각각의 linac 은 2DOF 를 가진 robot manipulator 에 달려있다. 그리고 구조적으로 linac 에서 나오는 beam 은 어떤 모습에서도 한 점을 가리키게 되어있다. 각 robot manipulator 는 서로 충돌하지 않으며 독립적으로 작동된다. 본 논문에서는 두 개의 LINAC 을 독립적으로 이용하는 simulation 을 통해 수술 시간을 단축시킬 수 있다는 것을 보일 것이고, 적은 DOF 의 robot manipulator 를 이용하며 LINAC 들이 한 점을 언제나 가리키는 구조적인 특징을 이용한 simulation 을 통해서 beam 의 높은 정확도에 대해 다룰 것이다.