Dose evaluation of organs at risk during treatment using gamma knife stereotactic radiosurgery (GKSRS): phantom study

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Abstract. Gamma Knife Stereotactic Radiosurgery (GKSRS) treatment requires the high accuracy of delivering single high dose without negative impact on the surrounding tissue. During radiosurgery treatments using GKSRS, the surrounding tissue will receive high scatter radiation because the single dose treatment will employed long irradiation time. Therefore, radiation doses in critical organs of patients during GKSRS treatment is important to be evaluated. In this study, we investigated the radiation dose to the lens, thyroid, breast, uterine fundus, ovaries and testes during treatment using Leksell Gamma Knife Perfexion (LGK; Elekta AB, Stockholm, Sweden). The dose was simulated using the variation of tumour target from 5 to 20 cc. The measurement were performed using variation of collimator size of 4 mm, 8 mm, 16 mm and employed thermoluminescent dosimeters (TLDs) to be placed at the surface of Rando anthropomorphic phantom. TLDs reader Harshaw model 3500 were employed to evaluate the measurement result. The result of this study explains that the dose of organs at risk decrease linearly depend on the distance of the target, target volume and the size of collimator.

1. Introduction
Stereotactic radiosurgery (SRS) is determined as a procedure that uses a beam of focused ionizing beam, and is given in a single fraction at high doses. Radiosurgery is a therapeutic choice that can be used for intracranial cases. Several cases that considered as radiosurgery is skull base tumors, small determining tumors, and slow proliferating tumors where the nature of these tumors is less responsive to conventional dose radiotherapy. High radiation dose in radiosurgery, tumor size is considered one of the things that need to be considered. This is caused by unexpected toxicity during high doses of radiosurgery with a large size tumor.

Leksell Gamma Knife (LGK) unit is specialized for stereotactic radiosurgery (SRS} and categorized as non-invasive destruction of an intracranial target [1]. LGK used 192 source of cobalt-60 and divided into 8 radiation sectors which is driven using a motor in each sector all rays gather at the isocenter to deliver radiation shots [2]. Gamma Knife Stereotactic Radiosurgery (GKSRS) has been used for definitive or adjuvant treatment of intracranial lesion, including some of primary benign tumor (acoustic...
neuroma, meningioma, and pituitary adenoma), trigeminal neuralgia, arterial malformations, pineal
tumors, pituitary tumors, vascular malformations \([3–6]\), vestibular schwannomas, brain metastases, and
gliomas. GKSRS treatment requires the high accuracy of delivering single high dose without negative
impact on the surrounding tissue. During radiosurgery treatments using GKSRS, the surrounding tissue
will receive high scatter radiation because the single dose treatment will employed long irradiation time.
Therefore, radiation doses in critical organs in patients during GKSRS treatment is needed to be
evaluated. In this study, we investigated the radiation dose to the lens, thyroid, breast, uterine fundus,
and ovaries and testes during treatment using Leksell Gamma Knife Perfexion (LGK; Elekta AB, Stockholm,
Sweden).

2. Experimental Methods
Measurements were made using rods TLDs \((1 \text{ mm} \times 6 \text{ mm})\). The TLDs (TLD-100; Harshaw/Bicron,
Solon, OH) were sorted into groups of equal sensitivity. This was accomplished by measuring the output
from each TLD using TLD Reader (Harshaw model 3500) after it was irradiated with 1 Gy irradiation
using Co-60 gamma rays (Cirus Cis Bio). The TLDs were annealed at 400 °C (Oven West 4100+).
Calibration was performed with irradiation doses in the range from 0.5 to 100 cGy, then calibration
curve and correction factors were obtained in terms of cGy/nC.

Figure 1. Head frame (a) and scalp measurement (b).

Figure 2. Phantom position during treatment.

Prior to the measurement, TLDs were sealed in a thin plastic envelope with sizes of 2.5 cm \(\times\) 1.5 cm
which consist of three TLDs with approximately equal sensitivity and took placed on the phantom
surface and fixed by tape at selected location. Treatment preparation was performed with installation of
head frame at anthropomorphic phantom (Alderson Rando Phantom, Alderson Research Laboratories,
Inc., Stamford, Connecticut) and geometry of phantom head measured using scalp measurement (figure
1). Magnetic Resonance Imaging (MRI) scanning was used to obtain the image of anthropomorphic
phantom and then transferred to Leksell Gamma Planning (LGP) to determine the target position and
dose distribution with the maximum dose of 36 Gy. LGK Perfexion system (Elekta AB, Stockholm,
Sweden) used to irradiate the anthropomorphic phantom. The target positioned at the center, and target
volume were varied from 5 cc, 10 cc, 15, and 20 cc as well as collimator size varied from 4 mm, 8 mm,
and 16 mm. The position of the phantom at treatment time is shown in Figure 2. Then the data of TLDs read out for selected organs were obtained.

3. Result

Measurement of radiation doses to organs at risk can be assessed by placing dosimeters within the organ of the phantom. Therefore, an approach is carried out by placing the TLD on the surface of lens, thyroid, breast, uterine fundus, ovary, and testes. Measurement of radiation doses to organs at risk with variation of target size expressed in centigray (cGy) are summarized in Table 1. Radiation dose for right and left side of phantom organs has discrepancy less than 1%. Figure 3 also show that radiation doses to organs at risk depend on the distance from the target and target volume. Radiation doses to the uterine fundus, ovary, and testes relatively same and significantly lower than radiation doses to the lens, thyroid, and breast. For the larger target volume 20 cc, the radiation doses to the lens, thyroid, and breast contribute 1.17%, 0.096%, and 0.041%, respectively, relative to the maximum target dose of 36 Gy while the doses to the uterine fundus, ovary, and testes contribute 0.022 %, 0.020 %, and 0.018 %, respectively, of the maximum target dose.

| Organs at risk | Dose (cGy) | 5 cc | 10 cc | 15 cc | 20 cc |
|---------------|------------|------|------|------|------|
| Lens          |            | 17.535 | 20.892 | 32.591 | 42.100 |
| Thyroid       |            | 2.154 | 2.801 | 3.272 | 3.439 |
| Breast        |            | 1.057 | 1.118 | 1.253 | 1.468 |
| Uterine Fundus|            | 0.727 | 0.776 | 0.846 | 0.789 |
| Ovary         |            | 0.655 | 0.627 | 0.772 | 0.702 |
| Testes        |            | 0.623 | 0.630 | 0.770 | 0.631 |

Beside depending on the distance and target volume, Figure 4 also explains that radiation doses to organs at risk depend on the collimator size. Radiation doses to the uterine fundus, ovary, and testes are significantly lower than radiation doses to the lens, thyroid, and breast. Table 2 shows that the radiation doses at organs at risk for larger collimator 16 mm contribute less than 0.3 % from the maximum target dose of 36 Gy. From the measurement result, it can be explained that radiation doses received to the organs at risk are accumulated from both leakage irradiation from LGK during treatment time, as well as the scattered irradiation to the organs at risk decrease with a larger distance from target, smaller target volume, and smaller collimator size.

| Organs at risk | Dose (cGy) | 4 mm | 8 mm | 16 mm |
|---------------|------------|------|------|-------|
| Lens          |            | 1.355 | 5.894 | 10.863 |
| Thyroid       |            | 0.814 | 1.055 | 1.539 |
| Breast        |            | 0.667 | 0.753 | 0.891 |
| Uterine Fundus|            | 0.630 | 0.673 | 0.677 |
| Ovary         |            | 0.609 | 0.628 | 0.624 |
| Testes        |            | 0.644 | 0.821 | 0.615 |

4. Discussion

In this study, radiation doses to organs at risk were measured in anthropomorphic phantom with LGK system at Gamma Knife Referral Centre, Cipto Mangunkusumo Hospital. Organs at risk during radiosurgery procedure is to be a concern especially in young pregnant patient.

The few studies dealing with this topic found out that the radiation doses in extracranial organs at risk depend on factors such as maximum target dose, numbers of isocenters, target volume, and collimator size. This study demonstrated that the radiation doses depend on the distance from the target,
target volume, and collimator size. Maarouf et al. [7] performed measurements of the absorbed doses to the extracranial organs at risk in patient undergoing Linac radiosurgery to the lens, thyroid, breast, ovary, and testes. They found out that the absorbed doses to the extracranial organs at risk were very low compared to dose constraint.

Table 3 shows that the absorbed doses in organs at risk during our study in anthropomorphic phantom area is well compared to the doses reported by gamma knife groups [1,3–11] and others using Linac [7]. Novotný et al. [4] found that there is an extra dose (transportation dose) received in the isocenter during patient transportation into and out of the treatment position. However, the dose is very low and it is not necessary to make any correction of the prescribed dose. According to Smedt et al. [9], total treatment time has a relatively important influence on extracranial doses. Nevertheless, on average, the absorbed doses to the extracranial organs at risk are relatively low.

![Figure 3](image3.png)

**Figure 3.** Plots of surface doses to organs at risk with variation of target volume.

![Figure 4](image4.png)

**Figure 4.** Plots of surface doses to organs at risk with variation of collimator size.
Table 3. Measured doses to organs at risk during radiosurgery (mean dose ± mean deviation in cGy), a comparison with literature.

| Study                  | Lens   | Thyroid | Breast | Fundus | Ovary Region | Testes |
|------------------------|--------|---------|--------|--------|--------------|--------|
| Berk et al. 1993 [3],  | 9±8    | 15±7    | 20±10  |        | 3 (gonads)   |        |
| GK                     |        |         |        |        |              |        |
| Novotný et al. 1996 [4]| 22.3±16.8 | 8.1±50  | 4.9±3.3 | 1.2±8  | (gonads)     |        |
| GK                     |        |         |        |        |              |        |
| Yu et al. 1997 [1],    | 35.7±30.8 | 20.6±8.9 | 21.4±12.1 | 4.1±2.7 | (pelvis)     |        |
| GK                     |        |         |        |        |              |        |
| Ma et al. 2000 [5],    | 8.1±0.6 |        |        |        |              | 8.1    |
| GK                     |        |         |        |        |              |        |
| Ioffe et al. 2002 [8], | 0.3516±0.4495 | 0.0966±0.0658 | 0.0388±0.0283 | 0.4170±0.3332 | 0.0063±0.0005 |        |
| GK                     | 0.0038±0.0283 |        |        |        |              |        |
| Smedt et al. 2004 [9], |        |        |        |        |              |        |
| GK                     |        |        |        |        |              |        |
| Maarouf et al. 2005 [7]| 22.7±20.1 | 15.5±8.4 | 4.7±2.3 | 2.0±1.2 | 0.90±0.36   |        |
| Linac                  |        |         |        |        |              |        |
| Hasanazadeh et al. 2006| 13.4±5.3 |        |        | 0.5±0.3 | 0.53±0.3     |        |
| [10], GK               |        |         |        |        |              |        |
| Gevaert et al. 2006 [11]| 43.57±8.72 | 10.32±2.06 | 4.78±0.96 | 0.59±0.12 | (gonads)     |        |
| [11], GK               |        |         |        |        |              |        |

According to several studies mentioned above, average radiation doses to organs at risk with variation of target volume lower compared to dose constraint. Similarly, this work found the same dose range of organ at risk. Radiation dose at the lens is larger than other organs at risk but it is still lower than maximum dose excess 1.5 Gy for single-dose exposure for cataract induction [3]. It is indicated that the dose for variation of target volume in the range from 42.1 cGy to 17.5 cGy and for variation of collimator size range from 10.863 to 1.355 compared to the maximum target dose.

Additionally, the most radiation-sensitive extracranial organs receive low doses during radiosurgery are the gonads, radiation exposure of the spermatogonia inhibits mitosis at low doses of 800 mGy causing temporary azoosperma. Furthermore, permanent sterility might be occurred at doses of 5 Gy. Therefore we conclude that the doses to the testes during radiosurgery are far below the above mentioned thresholds. Similarly, it is happen in female that the oocyte is less sensitive than the spermatogonium, but especially the mature oocytes are highly mutable [8]. ICRP in its report in 1990 had considered an equivalent dose limit of 2 mSv for pregnant patients in the reminder of pregnancy. Our data shows ovarian and testis doses are far from the limit dose. In general, the ICRP estimated the lifetime excess mortality due to radiation-induced cancer to amount to 4%/Sv which also depends on patients’ age. Taking the radiosurgery doses to thyroid and breast in this series into account with variation of target volume and collimator size, it could result an excess mortality about 1.17-0.017 %, respectively.

5. Conclusion
Radiation doses measurement to organs at risk in anthropomorphic phantom with gamma knife shows that radiation doses decreased linearly depend on the distance from the target, target volume, and
collimator size, and vice versa. From our study, we obtained that the radiation doses at organs at risk contribute less than 0.5% for variation of target volume and 0.04% for variation of collimator size, relative to the maximum target dose of 36 Gy. Overall, the measurement results show that GKSRS technically feasible modality and safe to treat patients especially for young and pregnant patients. However, special care and optimization must be taken to do a treatment planning with choice of collimator size and minimize the treatment time for consideration.

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