Verification of dose distribution on the gamma knife perfexion radiosurgery using gafchromic EBT3 film: RANDO phantom study

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Abstract. Leksell gamma knife (LGK) is an advanced modality of radiation therapy sourced Co-60 radioactive for treating patient with intracranial lesion. Small field techniques with highly integrated radiation delivering to patients in single session must be calculated accurately and verified carefully. This study illustrates a procedure to verify the accuracy of dose distribution associated with Leksell Gamma Plan (LGP) using RANDO phantom and gafchromic EBT3 film dosimetry. First, we assessed the profile dose on LGK standard phantom with collimators size 4, 8 and 16 mm and compared the results with the profile dose based on RANDO to obtained Full Width Half Maximum (FWHM) and beam-symmetry. Absorbed-dose distributions on RANDO with various combinations of lesion volume, collimator size, location and number of shots assessed by EBT3 film using LGK Perfexion. Scanned images of the measured films were processed following standard EBT3 film-handling procedures. Dose distribution calculation were performed using ImageJ software and MATLAB in-house software. The study shows different FWHM and beam-symmetry of collimator size of 16 mm on standard phantom between LGP and measurement is 1.83 % and 1.58 % whereas the discrepancy in RANDO phantom is 2.15 %, and 1.64 % respectively. Verification of max dose shows the smallest discrepancy on collimator size 16 single shot is 1.9 % on 7.61 cc superior lesion volume, where 12.12 Gy obtained by measurement and 12.36 Gy from LGP. In conclusion, collimator size 16 mm have a highest accuracy of FWHM and beam-symmetry value. However, on smaller lesion volume, collimator 16 mm with single shot give higher deviation dose value.

1. Introduction
Gamma Knife (GK) is a radiosurgery device consists of ⁶⁰Co gamma ray which is focused on a brain lesion by several collimator size. The new model Leksell Gamma Knife Perfexion (LGK PFX) introduced in 2006, has a completely different collimator system with respect to its predecessors. The PFX uses 192 sources which are organized into eight independent position-controlled movable sectors of 24 sources each. The stationary and built-in portion of the collimator system has three apertures for each source — 4, 8, and 16 mm [1,2]. Most GK radiosurgeries are performed in a single session; the typical maximum dose varies from 20 to 60 Gy for brain tumours or arteriovenous malformations and...
increases up to approximately 150 Gy for functional diseases [3]. Organs at Risk (OAR) that stay on proximity of pituitary gland are optic nerves, optic chiasm and brain stem that should be saved in the treating by ionizing radiation. Radiation therapy on cancer nearby healthy organs becomes a challenge. Treatment of intracranial lesion such pituitary adenoma with Gamma Knife radiosurgery immediately became popular, because of the ability of this technique to deliver the full treatment dose within one section and reducing risk of injury to nearby neural structure [4]. Small field techniques with highly integrated radiation given to a patient in a single session, the absolute value and relative distribution of the absorbed dose should be accurately calculated and carefully verified [3,4].

As radiotherapy modalities, verification of gamma knife equipment in clinical use must be carried out to ensure and evaluate the performance of the equipment in good condition. Simple verification of dose accuracy can be done using anthropomorphic standard phantom head [Elekta, A.B., Stockholm, Sweden] which consists a small hole to insert pieces of radiochromic film. The limitation of this verification only measured the profile dose of small pieces of radiochromic film [5]. Generally, the standard phantom for gamma knife dosimetry is composed of water-equivalent materials, such as acrylonitrile butadiene styrene (ABS). It does not represent the overall anatomy of the human head that consisting of bone density, soft tissue and air cavity [6]. Several studies of dosimetry in the gamma knife system have been carried out using radiochromic film or algorithmic approaches. One type of radiochromic film is gafchromic which has an effective atomic number composition equivalent to tissue, high spatial resolution, low energy effect, does not require chemical processes for film reading, not sensitive to visible light and measurement results can be stored permanently.

In 2017, Chung et al. in his study verifying the LGK dose profile with the convolution algorithm approach showed that the accuracy of the distribution of the dose profile in the collimator size variation, number of shots, and radiation location variation had a Gamma Index Pass Rate (GIPR ≥96.9%). This study shows that multiple shots have lower GIPR values than single shots [3]. Najafi et al. in the evaluation of the profile dose with gafchromic EBT in 4K model LGK using anthropomorphic heterogeneous head phantom (in house) shows the difference isocentre profile dose between LGP with the calculation is 5.8 ± 3.6% on the x-axis and 8.2 ± 6.7% on the y-axis [4]. This study illustrates a procedure to verify the accuracy of dose distribution associated with Leksell Gamma Plan (LGP) using RANDO phantom and gafchromic EBT3 film dosimetry. For this work, we proposed to see the accuracy of Full Width Half Maximum (FWHM), beam-symmetry and effect of tumor volume, collimator size, number of shots and shot location of the calculation.

2. Material and Methods
Several materials were used in this study are Leksell Gamma Knife Perfexion, Leksell Gamma Knife Standard Phantom, Exradin A16 micro ion chamber, Supermax Electrometer, Gafchromic EBT3 lot film #: 03208801 (expired March 2020), Epsom Perfection V700 Scanner, Anthropomorphic RANDO phantom, Magnetic Resonance Imaging (MRI) (GE Optima MR450w 1.5 T) and image processing software (MATLAB and ImageJ).

2.1. Calibration of Gafchromic EBT3 Film
Calibration of EBT3 gafchromic films was carried out on a 16 mm collimator using detector of Exradin A16 Micro Ion Chamber. Firstly, EBT3 gafchromic film were cut into 3.5 × 3.5 cm² and inserted on the Leksell Gamma Knife Standard Phantom. The EBT3 gafchromic film was calibrated with the same irradiation treatment time of 0.5,1,1.5,2,2.5,3,0.3,5,4,0,4.5 and 5.0 minutes as indicated in Figure 1. Absolute Dose values were obtained from supermax electrometer readings were described in Table 1.
Table 1. Absolute Dose measurement with standard phantom and Exradin A16 Micro Ion Chamber

| No. | Treatment Time | Average Dose (Gy) | STDV (Gy) |
|-----|----------------|--------------------|-----------|
| 1   | 0.5 min        | 1.477              | 0.001     |
| 2   | 1 min          | 2.969              | 0.001     |
| 3   | 1.5 min        | 4.435              | 0.001     |
| 4   | 2 min          | 5.937              | 0.001     |
| 5   | 2.5 min        | 7.393              | 0.001     |
| 6   | 3 min          | 8.903              | 0.004     |
| 7   | 3.5 min        | 10.35              | 0.004     |
| 8   | 4 min          | 11.863             | 0.006     |
| 9   | 4.5 Min        | 13.307             | 0.015     |
| 10  | 5 min          | 14.749             | 0.021     |

Figure 1. Calibration of EBT3 Film

After 48 hours irradiation, EBT3 films were scanned using the Epson Perfection V700 scanner with the TIFF image format and then evaluated using ImageJ and Matlab to obtain pixel values. Then, convert the pixel value into Net Optical Density (Net OD) to determine the dose value that can be written with the following equation 1 [7]:

\[
\text{Net OD} = \log_{10} \left( \frac{PV_{un}}{PV_{ex}} \right)
\]  

where \( PV_{un} \) and \( PV_{ex} \) is the average of the voxel values without irradiation and after irradiation. Furthermore, the calibration curve is determined by the third polynomial method, the results of the Net OD EBT3 film are converted to dose using a calibration curve equation [8]. Using the profile dose, Full Width Half Maximum (FWHM) and beam-symmetry values are verified on each collimator size in both phantoms and compared with Leksell Gamma Plan (LGP) values. To find the beam-symmetry value can be determined using the following equation 2:

\[
S = 100 \times \frac{\text{area}_{left} - \text{area}_{right}}{\text{area}_{left} + \text{area}_{right}}
\]
2.2. Scanning of RANDO Phantom
RANDO phantom has been scanned with a MRI to obtain cross-sectional and three-dimensional images of the RANDO phantom. EBT3 gafchromic film were inserted in the middle head slice of RANDO phantom. In order to ensure the fixation and accuracy of measurements, a stereotactic head frame was attached on RANDO phantom as illustrated in Figure 2(a) which consists of four screw pins. It is essentially applied to ensure there is no mobilization stereotactic head frame in the RANDO Phantom. Furthermore, head geometry measurements are made using a head bubble measurement as indicated in Figure 2(b), then the head geometry data will be put into the LGP device. The MRI image obtained sent to the LGP system in the DICOM format. From the MRI image data, the slice containing the EBT3 gafchromic film was made plan with variations on tumor volume, tumor location, collimator size and number of shots. Treatment on collimators size 4, 8 and 16 mm with a maximum dose of 12 Gy on the Leksell Gamma Knife Standard Phantom as illustrated in Figure 2 (c) was previously carried out for comparison of profile doses with the RANDO phantom as indicated in Figure 2 (d).

After the film scanned and stored in a digital file, the data was processed using the ImageJ and MATLAB programs. 2D dose distribution was determined by referring to the calibration curve as described in Figure 3. The dose value is obtained by making a Region of Interest (ROI) and then compared with each LGP dose.

![Figure 2. Stereotactic Head Frame (a) Head Bubble Measurement (b) LGK Standard Phantom Treatment (c) RANDO Phantom Treatment (d)]](image-url)
3. Result

3.1. Calibration Curve and Profile Dose Analyse
The calibration curve equation was determined by the absolute dose of the Exradin A16 Micro Ion Chamber irradiation and the netOD value of the EBT3 fitted with a third-order polynomial and obtained a determination value (R²) close to 1.0 as illustrated in Figure 3. Furthermore, Figure 4 shows the profile dose of each collimator was verified using standard LGK phantom and RANDO phantom then compared with LGP dose. LGK standard phantom shows the FWHM and beam-symmetry deviation values on 4 mm collimator are 3.69% and 5.26%, on 8 mm collimator of 2.49% and 3.22%, on 16 mm collimator of 1.83% and 1.58%. In the RANDO phantom, the smallest deviation with the LGP value is a 16 mm collimator with a deviation 2.15% and 1.63%.

3.2. Verification of Maximum Dose Value
Variations of tumour volume, tumour location, collimator size and number of shots were used as radiation parameters for this treatment. The results shows that on a single shot 16 mm collimator, the maximum dose deviation on central tumour volume of 4.04 cc is about of 7.19% whereas 13.14 Gy was obtained by measurement and 12.20 Gy from LGP, on lateral tumour volume of 6.46 cc is 4.02% where 11.66 Gy was obtained by measurement and 12.00 Gy from LGP and on superior tumour volume of 7.61 cc is 1.9% where 12.12 Gy was obtained by measurement and 12.36 Gy from LGP.

![Figure 3. Callibration Curve of EBT3 gafchromic film](image)

![Figure 4. Profile Dose of SWP and RANDO Phantom](image)
4. Discussions
Verification of dose value on the LGK Standard Phantom and RANDO Phantom are different, where the LGK Standard Phantom always has higher value than RANDO Phantom. It is due to the generally gamma knife Standard Phantom for dosimetry is composed of materials which are only equivalent to water whereas the RANDO phantom designed in the same shape as a human and composed by natural human skeletons, lung-like material, and soft tissue-like material that has the same absorption properties as human tissue at the level of exposure on radiotherapy [9] so that more doses were absorbed on this phantom.

Analysis of profile dose on collimator size of 16 mm shows different FHWM and beam symmetry values of standard phantom between LGP and measurement is about 1.83 % and 1.58 % respectively whereas the discrepancy in RANDO phantom is 2.15 %, and 1.64 % for FWHM and beam symmetry respectively and increased on smaller collimator sizes. This result is in line with yamauchi’s study that shows experimental results and LGP profiles compared in the case of 4 and 18 mm collimator is obvious that the discrepancy becomes more remarkable as the collimator size becomes smaller [10].

The smallest deviation of maximum dose value with collimator 16 mm single shoot irradiation showed on Superior tumour volume of 7.61 cc is about of 1.9% where 12.12 Gy obtained by measurement and 12.36 Gy from LGP as explained in Figure 5. The deviation is greater due to decreasing the size of tumour volume where the largest deviation at central tumour volume of 4.04 cc with 7.19% where 13.14 Gy obtained by measurement and 12.20 Gy from LGP. This result in line with Chung study that in analysis of all single shot dose distribution, the smallest differences between calculated maximum dose and measured were observed for the 16 mm whereas only 0.3 ± 0.9 % [3]. This is influenced by the greater size of the collimator for treatment on small volume tumours, so that many scattering doses affect the target dose. Superior position provides a better dose because the tissue characteristics at this position are more homogeneous unlike the central position where a spinal cord and even the sinus cavity or in the lateral region with uneven surfaces and more varied bone thickness.

5. Conclusion
LGK Standard Phantom always has higher dose value than RANDO Phantom. Collimator size 16 mm have good and smallest discrepancy of FWHM values and beam symmetry on standard phantom between LGP and measurement. However, with collimator size 16 mm single shoot on smaller tumour volume give the higher deviation of maximum dose.
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References
[1] Yuan, J. et al (2016). Development of a Monte Carlo model for treatment planning dose verification of the Leksell Gamma Knife Perfexion radiosurgery system. Clinical Medical Physics, Volume 17, Number 4.
[2] McDonald D, Yount C, Koch N, Ashenafi M, Peng J, Vanek K. Calibration of the Gamma Knife Perfexion using TG-21 and the solid water Leksell dosimetry phantom. Med Phys. 2011;38:1685–1693.
[3] Chung et al. (2017). Verification of dose profiles generated by the convolution algorithm of the gamma knife radiosurgery planning system. American Association of Physicists in Medicine. Med. Phys. 44 (9).
[4] Najafi, M. et al. (2018). Evaluation of dose profiles using Gafchromic EBT3 films in Leksell Gamma Knife 4C around inhomogeneities in the treatment of pituitary adenoma in anthropomorphic heterogeneous head phantom. Radiation Physics and Chemistry 149. 104–109.
[5] Natanasabapathia, G. and Bisht, RK. (2013) Verification of Gamma Knife extend system based fractionated treatment planning using EBT2 film. Medical Physics 40, 122104. doi: 10.1118/1.4832138
[6] Hornbeck, A. and Garciaa, T. (2014). Absolute calibration of the Gamma Knife Perfexion™ and delivered dose verification using EPR/alanine dosimetry. American Association of Physicists in Medicine. Medical Physics 41, 061708. doi: 10.1118/1.4873686
[7] Lee, A.W.M. et al., 2014. Evolution of treatment for nasopharyngeal cancer – Success and setback in the intensity-modulated radiotherapy era. Radiotherapy and Oncology, 110(3), pp.377–384. Available at: http://dx.doi.org/10.1016/j.radonc.2014.02.003.
[8] Borca, V.C. et al., 2013. Dosimetric characterization and use of GAFCHROMIC EBT3 film for IMRT dose verification. Journal of applied clinical medical physics, 14(2), pp.158–171.
[9] Federal, C. & This, W., 2012. RANDO ® Phantom M a n u a l. The Phantom Laboratory, pp.1–13.
[10] Yamauchi, M. et al. 2004. GAFChromatic film dosimetry with a flatbed color scanner for Leksell Gamma Knife therapy. American Association of Physicists in Medicine. Medical Physics. 31, 1243 (2004); doi: 10.1118/1.1712393