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Development and utility evaluation of new Multi-Leaf Collimator for Diagnostic X-ray Equipment

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Abstract – The diagnostic multi-leaf collimator preventing unnecessary dose from entering into patients during the diagnostic examination was made in this study. The movement of the entire 50 leaves was embodied with the group of 25 ones thereof configured in a pair facing each other on the left and right of the median line. Dimensions of the length, width, and height of each shielding leaf were $5\times0.5\times0.5cm^3$ resulting in the maximum boost field of $10\times10cm^2$. The material of multi-leaf collimator had the excellence on the machinability with the use of the SKD-11 alloy tool steel having the high wear resistance against frequent movement, and it was devised to control both-side's shielding leaves by moving 2 motors unlike existing remedial multi-leaf collimator that use as many motors as the number of 50 shielding leaves. Thereafter, the transmission dose of leaves, cross-leaf leakage dose, and inter-leaf leakage dose were measured by the developed multi-leaf collimator attached to X-ray equipment. An ionization chamber was used to detect doses there from, and the comparative analysis was carried out by means of the radiographic film that was easy to detect the dose leakage in between each leaf. Results obtained from the test conducted in comparative analysis yielded approximately 98%, 96%, and 94% of shielding efficiency realized at each level of energy of 80kV, 100kV, and 120kV it was confirmed there was no dose leakage resulted from the varied level of irradiation energy. Thus the multi-leaf collimator to be developed based on this study is thought that it could fully reduce the unnecessary dose to patients in the diagnostic test and the shielding efficiency thereof is expected to be increasing if it is made in a miniaturized form with a way of increasing the thickness of each leaf later for an extended application to general diagnostic purposes.

Keywords: Diagnostic multi-leaf-collimator, Ionization chamber, Gafchromic film, Dose reduction, Shielding

1. Introduction

Many studies have been conducted so far to find ways to reduce the dose of irradiation to patients in a diagnostic examination. The methods directly applying the leads to surface of patients' body taking computerized tomography or dental radiography have been reported to shield sensitive eyes or thyroid gland from irradiation [1-8]. Contrastingly, the number of cases of exploiting the multi-leaf collimator which has been actively employed for the radiotherapy to the diagnostic purposes are relatively few. Multi-leaf collimator is a shielding system consists of many shielding leaves the idea thereof was first introduced into radiological equipment by Rbinsohn et al. in 1906. Since then, Gscheidlen et al. had devised the multi-leaf collimator for radiotherapy in 1959 [9-11]. Takahashi in Japan has been known as the first one applied the multi-leaf collimator to the clinical stereo-radiographic therapy in 1965 [12]. Comparing to existing shields made of lead, the multi-leaf collimator has advantages of the convenience in reduced period of time for making each shield for respective various boost fields by avoiding individual preparations there for [13]. However, in cases of making desired therapeutic radiation field by using the multi-leaf collimator, there was a problem of the potential transmission dose to be created in between the leaves thereof thereby, diverse studies that explored the characteristic distribution of dose there from have been carried out [14-15]. Therefore, in this study, the multi-leaf collimator capable of making variable shapes of shielding for diagnostic purposes was developed based on the technology used to produce the multi-leaf collimator currently employed for radio-therapeutic purposes. The developed multi-leaf collimator was then attached to the X-ray equipment currently used in clinics and the transmission dose of leaf, the cross-leaf leakage dose, and the inter-leaf leakage dose were measured to assess the effects thereof and to evaluate the utility of the developed multi-leaf collimator in diagnostic purposes.

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2. Design and Implementation of Multi-leaf Collimator for Diagnosis

For the implementation of the multi-leaf collimator developed in this study, efforts were focused on realizing its capability of making variable shapes of shielding to reduce the dose leakage there from to unnecessary fields beyond targeted diagnostic area.

2.1 Engineering design and fabrication of multi-leaf collimator

As illustrated in Fig. 1(c), the geometric structure of multi-leaf collimator prepared for diagnostic purposes is comprised of a total of 50 leaves arranged in a pair of respective groups of 25 leaves confronting each other on both sides of the median line thereof. Each pair was enabled to move individually and dimensions of the length, width, and height thereof were 5×0.5×0.5cm^3 by which, the maximum boost field of 10×10cm^{2}was realized. Due to the design of the multi-leaf collimator that enabled individual leaves to move independently to make desired shielding, there can be potential leakage of radioactive rays in between the leaves [16-17]. Hence the side of leaves were designed to be parallel to the beam, and to prevent the leakage of radioactive rays in between the leaves the side of leaves were configured with a shape of stairway rather than leaving it in a planar shape, and as illustrated in Fig. 1(b), the mating leaves adjacent each other were also enabled to move parallel to each other. Fig. 1(a) shows the 3D model of multi-leaf collimator generated and completed by the 'Solidworks' program. For the shielding material to be used for the fabrication of multi-leaf collimator, the alloy SKD-11 which shows its density similar to that of iron was used. SKD-11 contains carbon (1.6%), silicon (0.4%), manganese (0.6%), chromium (5%), molybdenum (1%), and vanadium (0.3%) its density is 7.89 g/m^3. SKD-11 exhibits an excellent machinability by which the fabrication of precision multi-leaf collimator is enabled and the high wear resistance of leaves made thereof can guarantee users a long lifetime availability despite frequent movement thereof required for making diverse shapes of shield.

2.2 Multi-leaf collimator controller

Existing controllers made to control the multi-leaf collimator are designed in a way to control individual

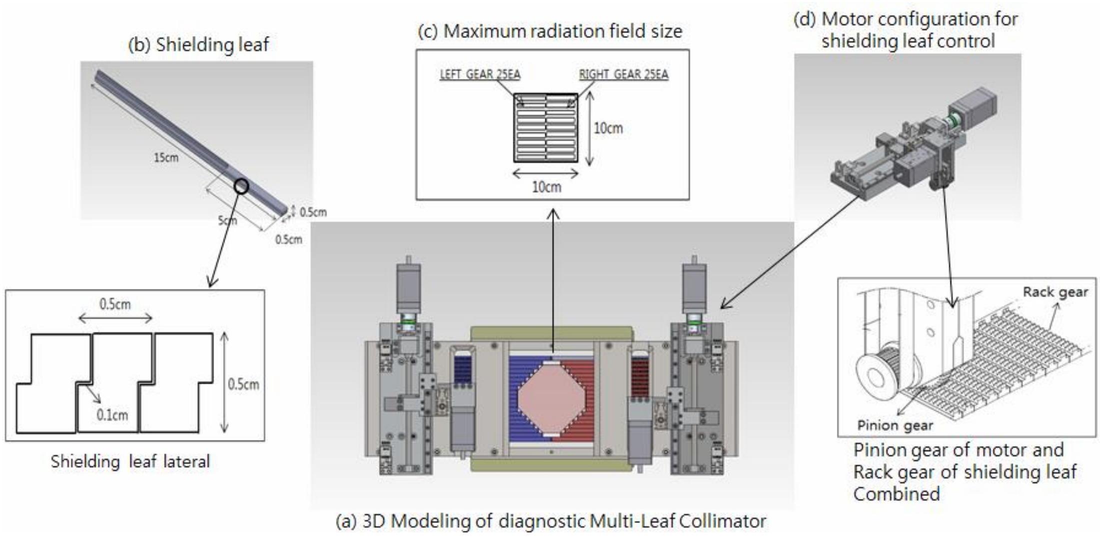
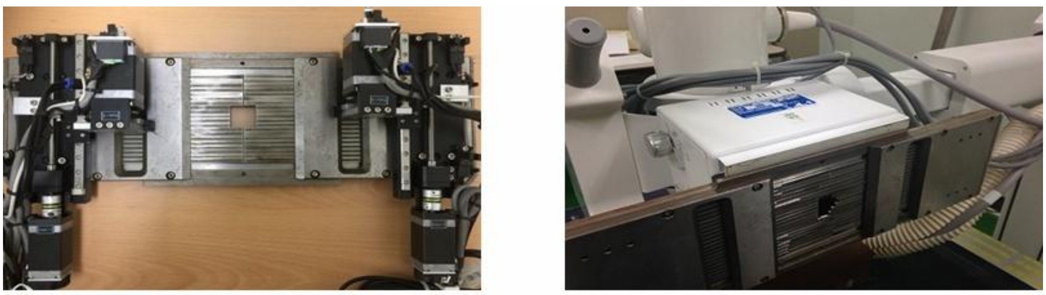


Fig. 1. Engineering design of diagnostic multi-leaf collimator



(a) Produced diagnostic Multi-Leaf Collimator

(b) diagnostic Multi-Leaf Collimator attached to the diagnostic radiation equipment

Fig. 2. Produced diagnostic multi-leaf collimator and attach the diagnostic radiation equipment

leaves therein through motors dedicated to each leaf making the system configuration of motor drivers and control thereof more complex requiring expensive costs. To complement these disadvantages, the multi-leaf collimator developed in this study was designed to employ the 6-axis actuator (4 axes for motor and 2 axes for the pneumatics) enabled to configure desired shapes of shield with the control of the 50 leaves therein. For the operation of corresponding motors, the rack gear and pinion gear were coupled, and each leaf is supposed to be moving by a sequential shift of the stepping motor equipped with a pinion gear. The stepping motor equipped with screw axis is thus can be activated to shift itself sequentially to join with the rack gear of each leaf and by the repetition of this operation, the multi-leaf collimator can be controlled effectively. Thus, contrasting to existing multi-leaf collimators using the number of motors as many as the number of equipped leaves, only the two cost-effective motors are needed to control the entire leaves in the multi-leaf collimator. Fig. 2(a) illustrates the multi-leaf collimator equipped with the controller wherein the pair of 3-axis actuators enabled to control the unit of 25 leaves, the leaves of multi-leaf collimator, the body thereof, the timing belt and gear wheel made for the shift of the leaves, and the latch designed to hold the leaves on both sides during the shift are shown.

3. Evaluation of the Utility of Developed Multi-leaf Collimator

The transmission dose of leaf, the cross-leaf leakage dose, and the inter-leaf leakage dose of the multi-leaf collimator developed in this study were measured to examine the effects and shielding efficiency and to evaluate the diagnostic availability thereof. For the test of diagnostic shielding efficiency, the developed multi-leaf collimator was mounted under the general radiographic equipment (Rex-650R, Listem, KOREA). The multi-leaf collimator was positioned on the median line 10cm distant from the detector as shown in Fig. 3. Thereby, the distribution of dose generated at each state of completely opened and complete closure of the multi-leaf collimator was compared. The Ionization Chamber (Farmer Type Ionization Chamber, Radcal9015) and the Gafchromic Film(Gafchromic XRQA2 Film, USA) which was convenient to detect the dose leakage in between the leaves were employed for the test and comparative analysis.

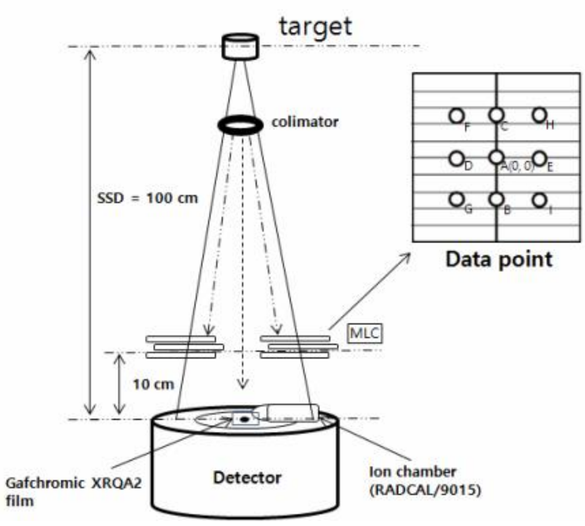


Fig. 3. Experimental Setup for evaluation of utility of the diagnostic multi-leaf collimator with ion chamber (Data point refer to measurement point using ion chamber

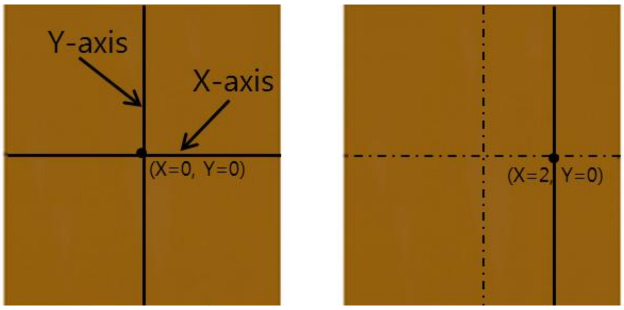
3.1 Measurement of dose using an ionization chamber

For the test of transmission dose from the developed multi-leaf collimator, the ionization chamber was put on the position 10cm distant from the multi-leaf collimator with the source-surface distance set 100cm and the point doses in the air generated at each state of completely opened and complete closure of the multi-leaf collimator were measured, compared, and appraised thereby. As illustrated in the “Data point” in Fig. 3, the nine (9) coordinates of the measurement points (x cm, y cm) were determined A(0, 0), B(0, -2), C(0, +2), D(-2, 0), E(+2,0), F(-2, +2), G(-2, -2), H(+2, +2), and I(+2, -2) including the center point A(0, 0) by considering the transmission dose in cross-leaf and at inter-leaf. The test was carried out by applying varied levels of the irradiation energy of 50mAs 80 kV, 50mAs 100 kV, and 50mAs 120 kV repeated five (5) times respectively from which, the respective mean values of each measurement were taken as the value of measurement.

3.2 Measurement of dose distribution using radiographic film

The measurement of dose distribution using radiographic film was carried out under equally applied conditions by placing the radiographic film on the position same with that of the placement of ionization chamber. The film scanner (Epson Expression 1680 Pro, Epson, Japan) was used for the test and the images which were scanned as a form of reflected document of the mode of 48 bit RGB – 75(dpi) were stored in the form of lossless compression image of the TIFF(Tagged Image File Format).To remove the dependency on the scanning position and direction of the film scanner, the center of the film to be scanned was aligned with the center of the scanner. On completion of each scan, the software developed spontaneously for the analysis of dose distribution was used to measure the dose distribution on boost field of the film made by the multi-leaf collimator.

As illustrated in Fig. 4, every pair of the leaves of multi-leaf collimator were closed completely in a way they are aligned with the median line (X=0), and thereafter, the distribution of PV (Pixel Value) of the points on x-axis was measured by fixing the inter of every pair of the leaves on the point Y=0 to measure the distribution of transmission dose in between the leaves. Thereafter, by applying the same condition, the distribution of PV on points of the y-axis was measured by fixing the inter of every pair of the leaves were fixed on the point X=0. The same condition was applied to the measurement of the dose distribution in between the leaves of multi-leaf collimator as well. In a way of fixing the leaves on the point X=2cm, the distribution of PV on points on the y-axis was measured.



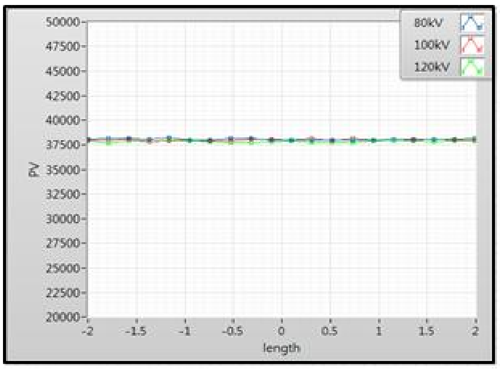
(a) Inter-leaf (b) Cross-leaf

Fig. 4. Coordinate to measure dose distribution by transmission dose of diagnostic multi leaf collimator in the gafchromic film (a) Inter-leaf (b) Cross-leaf

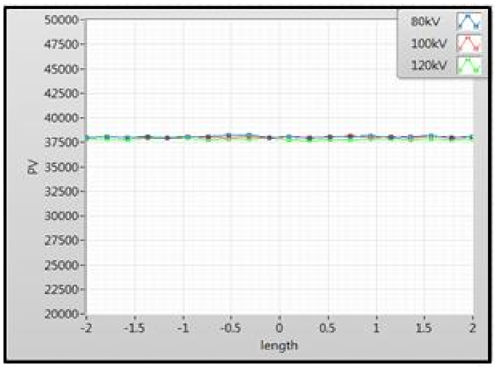
4. Results of the Evaluation of Utility

4.1 Rates of transmission dose of multi-leaf collimator measured with ionization chamber

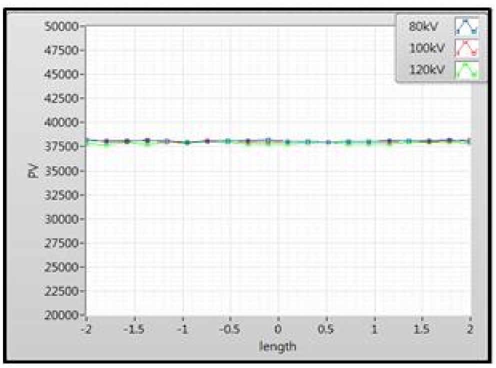
The position of ionization chamber employed for the measurement of transmission does in cross-leaf and at inter-leaf was determined by taking the account of both doses by which the transmission does at the inter-leaf was measured mainly on the points of A, B, and C to which a certain extent of the transmission dose in between leaves was contributed. On the points of D and E, the transmission dose in between the leaves was measured solely. On the points of F, H, H, and I, the transmission dose from each leave was measured. Results obtained from the measurement of transmission dose showed the values of mean and standard deviation of point dose less than 0.11 that appeared uniformly on the whole irrespective of the varied positions of measurement conducted with the complete closure of the multi-leaf collimator. Since the



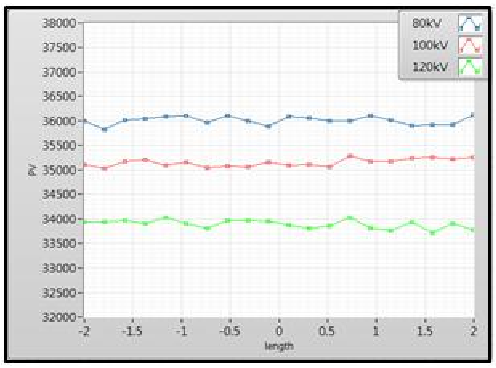
(a) Dose distribution between longitudinal leaves in MLC field (X-axis)



(b) Dose distribution between longitudinal leaves in MLC field (Y-axis)



(c) Dose distribution leaf side in MLC field



(d) Dose distribution in open field

Fig. 5. Comparison of Dose distribution on diagnostic multi-leaf collimator in each case of MLC field and open field (80 kV, 100 kV, 120 kV)

level of transmission dose measured with the diagnostic equipment employed in the test was lower than that of the radiotherapy equipment, no leakage of transmission dose at each level of diagnostic energy level in between the engaging leaves was identified. By using the ionization chamber, the shielding efficiency of multi-leaf collimator in the state of complete closure was measured as percentage values of point dose measured at each point to the value obtained from the state of completely opened multi-leaf collimator taken as reference value there for. The resulted values of the shielding efficiency were approximately 98%, 96%, and 94% gradually decreased in accordance with the increasing level of energy: 50 mAs 80 kV→50 mAs 100 kV→50 mAs 120kV. The values corresponded to levels of the energy of 80 kV and 100 kV appeared beyond 95% of the shielding efficiency of generally used shields.

4.2 Distribution of transmission dose of multi-leaf collimator detected through radiographic film

Measurements of PV (Pixel Value) were compared with the length of boost field and then plotted on a graph wherein the linearly plotted points different from the points plotted in wavy forms typically resulted from an engagement of adjoining leaves can be found from Fig. 5(a), 5(b), and 5(c). In this way, no dose leakage in between the adjoining leaves was identified. Fig. 5(d) shows the dose distribution plotted according to measurements obtained at each level of energy of 80 kV, 100 kV, and 120 kV from the completely increased in accordance with the increasing level of energy.

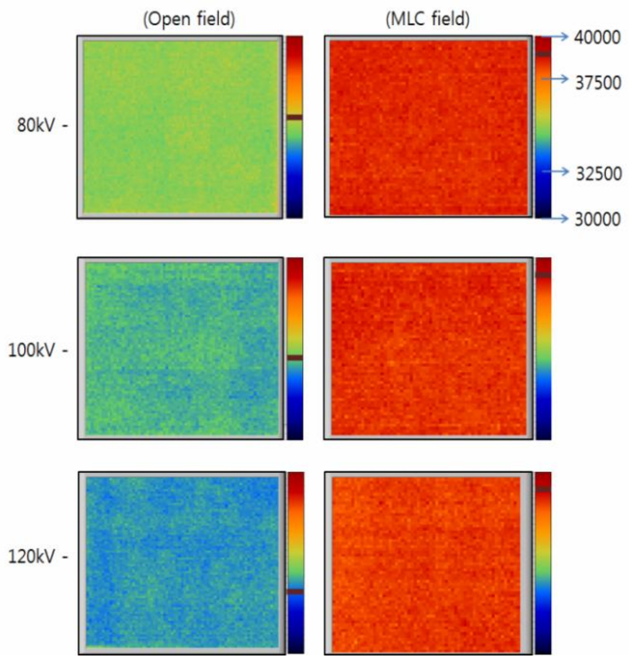


Fig. 6. Color Mapping of Dose Distribution resulted from the diagnostic Multi-leaf Collimator (Open field and MLC field)

Fig. 6 shows the picture of radiographic film of which range of the fields irradiated at each level of energy of 80 kV, 100 kV, and 120 kV from the multi-leaf collimator situated at both states of completely opened and complete closure are mapped to corresponding colors.

The color mapping of the state of completely opened multi-leaf collimator shows the PVs decreasing in accordance with the increasing level of energy with the color thereof becoming darker. The image of radiographic film was getting darker by the dose increased in accordance with the increasing level of energy. Whereas, the color mapped image made with complete closure of the multi-leaf collimator shows no significant difference in the intensity of its color irrespective of the changing level of energy. In addition, a dose leakage frequently ascribable to the attribute of the multi-leaf collimator was not found.

For the calculation of shielding efficiency, the PV of radiographic film unexposed to radioactive ray was taken as the background value from which the difference to the PV of film image irradiated with the complete closure of multi-leaf collimator was calculated. Calculations resulted thereby were 20.9±1.3, 29.6±1.1, and 42.1±1.5 at each energy level of 80 kV, 100 kV, and 120 kV. In the case of the complete closure of multi-leaf collimator, the calculations were 0.37±0.5, 0.99±0.5, and 2.52±0.5 corresponded to each level of energy of 80 kV, 100 kV, and 120 kV. The value of shielding efficiency is represented as a percentage of the difference in point dose measurements obtained at each point with the complete closure of multi-leaf collimator. They were 98.23%, 95.64%, and 94.02% at each level of energy of 80 kV, 100 kV, and 120 kV thus the shielding efficiency appeared higher correspondingly to the lower level of energy, as presented in Table 2.

Table 1. Shielding rate of diagnostic multi leaf collimator using the ionization chamber depending on the tube voltage (mGy, mean ±S.D)

Tube Voltage (kV)	Open field (mGy)§	Close field (mGy)§	Shielding rate(%)*
80	4.93 ± 0.06	0.089 ± 0.001	98.19
100	6.27 ± 0.07	0.203 ± 0.004	96.76
120	7.33 ± 0.11	0.373 ± 0.01	94.91

Table 2. Shielding rate of diagnostic multi leaf collimator using the Gafchromic film depending on the tube voltage (Pixel value, mean ±S.D)

Tube Voltage (kV)	Open field (PV)§	Close field (PV)§	Shielding rate(%)*
80	20.9 ± 1.3	0.37 ± 0.5	98.23
100	29.6 ± 1.1	0.99 ± 0.5	96.64
120	42.1 ± 1.5	2.52 ± 0.5	94.02

§ means and standard deviations of the measurement of five repetitions

$$\text{*Shielding rate (\%)} = \left[1 - \frac{\text{Close field Value}}{\text{Open field Value}} \right] \times 100$$

5. Conclusions

In the clinical diagnostic examinations, the shields made of lead (Pb) or bismuth have been frequently used to shield internal organs from unnecessary dose of irradiation within the cope avoiding effects thereof to the diagnosis.

This study intended for the development of the new type of multi-leaf collimator based on the technology of current ones employed in radiotherapy systems to protect normal internal organs. Current commercial multi-leaf collimators typically use the automatized individual motor control over individual leaves to make boost fields similar to shapes intended for respective treatments. However, the operation of independent motors installed as many as the number of each leaf makes current ones disadvantageous in that the size thereof is increasing as well as the increasing cost of operation. With the use of current multi-leaf collimator, the availability in making the shapes for boost fields is limited to the sections similar to shapes of stairways of the sizes ranging1.00~1.25 cm depending on the size of each leaf thereby, the shapes of irradiation fields resulted there from cannot be elaborated accurately as the ones made with shields of lead alloy.

In addition, the transmission dose to be generated in between each leave in multi-leaf collimator may cause troubles in making the desired shape of therapeutic irradiation fields. Thus to minimize the generation of transmission dose, the leaves should be arranged as closely as possible with the interfaces in between the leaves to be of the shape of stairways to prevent the direct penetration of radioactive rays. Hence, the design of new diagnostic multi-leaf collimator developed in this study was conceived by taking the advantages of existing technologies of making multi-leaf collimators and the schemes enabled to complement disadvantages thereof into account.

Different from existing radiotherapy multi-leaf collimators employing the leaves of 10cm thickness, the lower level of energy required for diagnostic purposes of the multi-leaf collimator to be developed in this study were taken into account, and thereby, the thickness of each leaf was determined 0.5cm with 0.5cm of the width thereof to enable the creation of accurate boost field. The SKD-11 alloy tool steel was employed for the fabrication of multi-leaf collimator since it exhibits excellent machinability and wear resistance against frequent motions of parts made there from. Besides, the independent motor control over respective 50 leaves was excluded by taking the combined two-motor control over a pair of groups of 25 leaves situated on both sides of the multi-leaf collimator. The developed multi-leaf collimator was then mounted on X-ray equipment and thereby, the transmission doses from each leaf, in cross-leaf, and at inter-leaf were measured.

An ionization chamber was used as a detector for transmission doses with the radiographic film intended for the measurement and comparison of transmission doses in between the leaves. Results obtained from the test conducted in this study showed the shielding efficiency thereof ranged 94% ~ 98% with no detected dose leakage. The efficiency is similar to the shielding efficiency of 95% of generally used shields [18]. Thus the multi-leaf collimator developed in this study is expected to be used for diagnostic examination purposes by preventing patients from being exposed to unnecessary doses. Further studies on the subjects of miniaturization of multi-leaf collimator and improvement of shielding efficiency are thus being considered for the extended application of the schemes to be developed thereby to the diagnostic disciplines.

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References

[1] Tsapaki V, Aldrich JE, Sharma R, Staniszewska MA., Krisanachinda A. et al. "Dose reduction in CT while maintaining diagnostic confidence: diagnostic reference levels at routine head, chest, and abdominal CT-IAEA-coordinated research project," *Radiology*, vol. 240, no. 3, pp. 828-834, Jul. 2006.

[2] Han S, Lee B, Shin G, Choi J, Kim J et al. "Dose area product measurement for diagnostic reference levels and analysis of patient dose in dental radiography," *Radiat Prot Dosim*, vol. 150, no. 4, pp. 523-531, Dec. 2012.

[3] Shortt, C. P., Fanning, N. F., Malone, L., Thornton, J., Brennan, P. and Lee, M. J. "Thyroid dose during Neurointerventional procedure: does lead shielding reduces the dose?" *Cardiovascular Interv Radiol*, vol. 30, no. 5, pp. 922-927, May. 2007.

[4] Han SC, Kwon SC. "Radiation dose reduction to the critical organ with bismuth shielding during endovascular coil embolisation for cerebral aneurysms," *Radiat Prot Dosim*, vol. 156, no. 3, pp. 364-371, Mar. 2013.

[5] Hopper, K. D., Neuman, J. D., King, S. H. and Kunselman, A. R. "Radioprotection to the eye during CT scanning," *AJNR Am J Neuroradiol*, vol. 22, no. 6, pp. 1194-1198, Jun. 2001.

[6] McLaughlin, D. J. and Mooney, R. B. "Dose reduction to radiosensitive tissues in CT: do commercially avail available shields meet the users' needs?" *Clinical Radiology*, vol. 59, no. 5, pp. 446-450, June. 2004.

[7] Moritake, T., Matsumaru, Y., Takigawa, T., Nishizawa, K., Matsumara, A. and Tsuboi, K. "Dose measurement

on both patients and operators during Neurointerventional procedures using photo-luminescence glass dosimeters," *AJNR Am J Neuroradiol*, vol. 29, no. 10, pp. 1910-1917, Aug. 2008.

[8] Prins, R., Dauer, L. T., Colosi, D. C., Quinn, B., Kleiman, N., Bohle, G., Holohan, B., Al-Najjar, A., Fernandez, T., Bonvento, M. et al. "Significant reduction in dental cone beam computed tomography (CBCT) eye dose through the use of leaded glasses," *Oral Surg Oral Med Oral Pathol Oral Radiol Endod*, vol. 112, no. 4, pp. 502-507, Jul. 2011.

[9] Khan FM. "Treatment planning Ⅲ: The physics of radiation therapy," *Baltimore/Lodon Williams & wikins*, pp. 320-323, 1994.

[10] Robins hn I. "Apparat zur radiologischen Belichtung lebender under lebloser Objekte," *German patent nr*, pp. 192-300, 1906.

[11] S Webb. "The physics of three-dimensional radiation therapy," *Institute of physics publishing Bristol and Philadelphia*, pp. 218-245, Jan. 1993.

[12] Kitabatake T. "Development of telecobalt therapy unit with a new collimation device for conformation radiotherapy," *Nippon actaradiol*, vol. 26, pp. 192-200, 1996

[13] Helyer SJ, Heisig S. "Multileaf collimation versus conventional shielding block : a time nad motion study of beam shaping in radiotherapy," *Radiotherapy and Oncology*, vol. 37, no. 1, pp. 61-64, Oct. 1995.

[14] LoSasso T, Chui Cs, Kutcher GL, Leibel SA, Fuks Z, Ling CC. "The use of a multi-leaf collimator for conformal radiotherapy of carcinomas of the prostate and nasopharynx," *lnt J Radiation Oncology Biol Phys*, vol. 25, no. 2, pp. 161-170, Jan. 1993.

[15] Powlis WD, Smith AR, Cheng E, et al "initiation of multileaf collimator conformal radiation therapy," *int J Radiation Oncology Biol Phys*, vol.25, no.2, pp. 171-179, Jan. 1993.

[16] Galvin JM, Smith AR, Moeller RD. "Evaluation of multileafcollimatior design for photon beam," *lnt J Radiation Oncology Bio lPhys*, vol. 23, no. 4, pp. 789-801, 1992.

[17] Boyer Al, Ochran TG, Nyerick CE, Waldron TJ, Huntzinger CJ. "Clinical dosimetry for implementation of a collimator," *Med phys*, vol. 19, no. 5, pp. 1255-1261, Sep. 1992.

[18] Huq MS, Yu Y, Chen ZP, Suntharalingam N "Dosimetric characteristics of a commercial multileaf collimator," *Med Phys*, vol. 22, no. 2, pp. 241-247, Feb. 1995.

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