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Feasibility Study of a Custom-made Film for End-to-End Quality Assurance Test of Robotic Intensity Modulated Radiation Therapy System

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This paper aims to verify the clinical feasibility of a custom-made film created by a laser cutting tool for End-to-End (E2E) quality assurance in robotic intensity modulated radiation therapy system. The custom-made film was fabricated from the Gafchromic EBT3 film with the size of 8"×10" using a drawing that is identical to the shape and scale of the original E2E film. The drawing was created by using a computer aided design program with the image file, which is obtained by scanning original E2E film. Beam delivery and evaluations were respectively performed with the original film and the custom-made film using fixed-cone collimator on three tracking modes: 6D skull (6DS), Xsight spine (XS), and Xsight lung (XL). The differences between total targeting errors of the original and custom-made films were recorded as 0.17 mm, 0.3 mm, and 0.17 mm at 6DS, XS, and XL tracking modes, respectively. This indicates that the custom-made film could yield nearly equivalent results to those of the original E2E film, given the uncertainties caused by distortions during film scanning and vibrations associated with film cutting. By confirming the clinical feasibility of a custom-made film for E2E testing, it can be expected that economic efficiency of the testing will increase accordingly.

Key Words: End-to-End test, Quality assurance, CyberKnife, Robotic IMRT

Introduction

Robotic intensity modulated radiation therapy (IMRT) M6 (Fig. 1), the latest CyberKnife system that is aimed at providing ultimate precision in the stereotactic radiation surgery and stereotactic body radiation therapy techniques,[1-5] was adopted and is being put to operation for the first time in Asia by Yonsei Cancer Center.[6] As the 5th generation of CyberKnife system following its older generations G2, G3, G4, and VSI, the robotic IMRT M6 system is equipped with three types of collimators including the 10 cm×11 cm multileaf collimator (MLC), the 12-aperture fixed-cone collimator, and the variable aperture IRIS collimator.[7] By selecting the proper collimator when planning a treatment, precise performance can be achieved according to tumor size and shape, and the 6-axis robotic arm moving freely around the target area delivers the prescribed dose to the tumor with an accuracy of less than 0.95 mm. Furthermore, this system can track tumors that move with respiration during radiation therapy by means of X-ray images continuously obtained from the X-ray sources on the ceiling of the treatment room. At the same time, by using its synchrony camera, it can also calibrate errors of the movement caused by the respiration of a patient. Due to these characteristics as well as its enhanced precision and accuracy in treatment, the robotic IMRT M6 system is advantageous over other systems such as TomoTherapy and linear accelerator where

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motion compensation is hardly possible to achieve.

The report of the American Association of Physicists in Medicine (AAPM) Task Group 135, which describes the quality assurance for robotic radiosurgery, advises that record keeping of quality assurance testing and quality control procedure during adoption of new treatment technology or equipment is essential for efficiency improvement and risk reduction.[8] Therefore, the End-to-End (E2E) quality assurance testing is an indispensable stage to examine target location errors in tumor tracking. E2E testing is performed on three static tracking modes such as 6D Skull (hereafter 6DS), Fiducial, and Xsight spine (hereafter XS) modes and two motion tracking modes such as Xsight lung tracking (hereafter XLT) and synchrony respiratory modes.[8-10] E2E testing and analysis were performed using E2E film corresponding in size to each mode. Yonsei Cancer Center is currently conducting the film-based E2E test as a monthly quality assurance (QA) on all the three modes, i.e., the Fixed-cone, IRIS, and MLC modes. This, in turn, leads to increased film consumption and thus a pronounced need for time and economic efficiency to ensure a reliable supply of films.

Therefore, in this study, a custom-made film for E2E testing was fabricated from Gafchromic EBT3 film (Ashland, Wayne, NJ),[11] and the static tracking 6DS and XS modes as well as the motion tracking XLT mode with fixed-cone collimator were performed to verify the applicability of the custom-made film. E2E testing was conducted for each mode employing original E2E film and custom-made film at the same time, and the results were compared to each other to verify whether E2E testing can be performed with a custom-made film.

Materials and Methods

1. E2E testing film fabrication

E2E testing films can be divided into four types according to their shape: 6 cm×6 cm A-L (anterior-lateral) film and A-S (anterior-superior) film used in the 6DS tracking, fiducial tracking, and synchrony respiratory modes; 3 cm×3 cm hexagonal-shaped film in the XS tracking mode; and 3 cm×3 cm cross-shaped film in the XLT mode. For each test, films are inserted alternately into a phantom in the directions corresponding to A-L and A-S. As for the directionally independent hexagonal-or cross-shaped films, a pair of films are employed alternately.

Each film was scanned and saved as a JPG file with an image format of 24-bit color depth and 1200 dpi resolution to create a drawing. EPSON Expression 11000XL capable of film and document scanning was used for this study. The drawing was created by importing the image files of scanned films using Q-CAD (version 3.7), one of the computer-aided design (hereafter CAD) software applications (Fig. 2). The drawing prepared was able to be saved in the drawing interchange for-

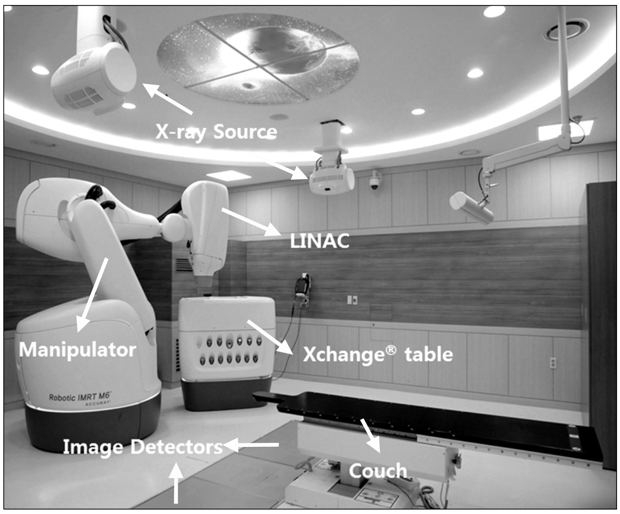

Fig. 1. Overview of robotic IMRT M6 system.

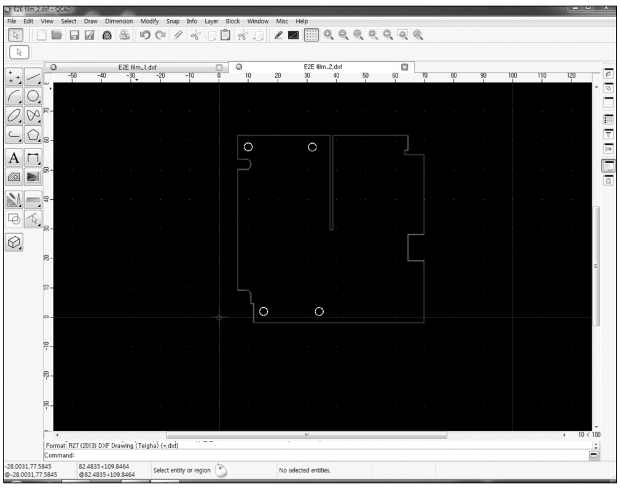

Fig. 2. Drawing an assembly diagram for E2E test (using Q-CAD program).

mat (DXF), which is compatible with Newlydraw1.5 software interconnecting to a laser cutting cutter used for this study (Microlaser C40, CORYART, Fig. 3).

2. Film cutting

Laser cutting machine with a low output power of 40 watts (W) used in cutting films for this study produces CO_2 laser, one of the gas lasers. Its repeatability and positioning accuracy are 0.01 mm, respectively.[12,13)]

Several parameters were set prior to film cutting. The film drawing created with Q-CAD was imported into Newlydraw1.5 software, which is compatible with the laser cutter, to determine the size and the area of the film to be cut (Fig. 4). The laser cutting start point of the laser cutter was set to start from the upper left corner. An 8 inch×10 inch EBT3 film was positioned at the start point, and the area to be cut was converted to centimeters and set at 20.3 cm×25.4 cm. Laser cutting was set to start at the point 3 cm on x-axis, 3 cm on y-axis off the upper left corner in order to allow a sufficient margin for the area to be cut, while the laser speed and step distance were set at 50 mm/s and 10 mm, respectively (Fig. 5). The parameters such as laser speed and intensity were determined in such a way as to minimize possible surface damage associated with EBT3 film cutting. In this study, the laser speed was set at 100 mm/s and the laser power was set to generate up to 30% of the maximum electric power 40 W (Fig. 6). The film arrangement was made in a way that a sin-

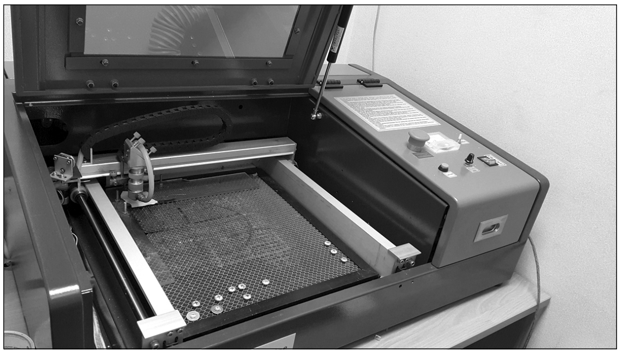

Fig. 3. Laser cutting machine (Microlaser C40, CORYART).

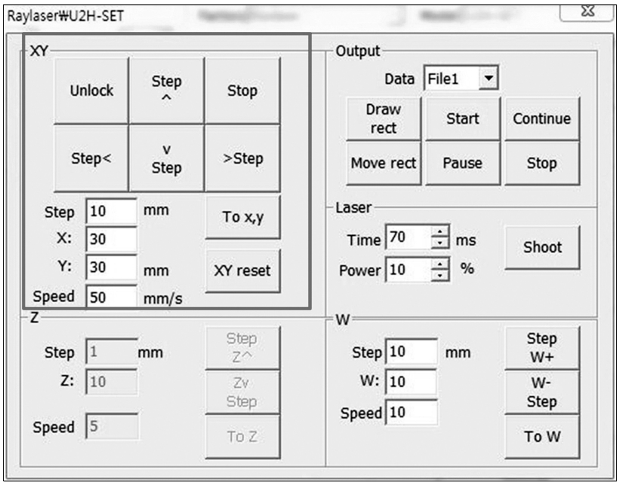

Fig. 5. Setting parameters: laser cutting start point, step distance, laser speed, and so forth.

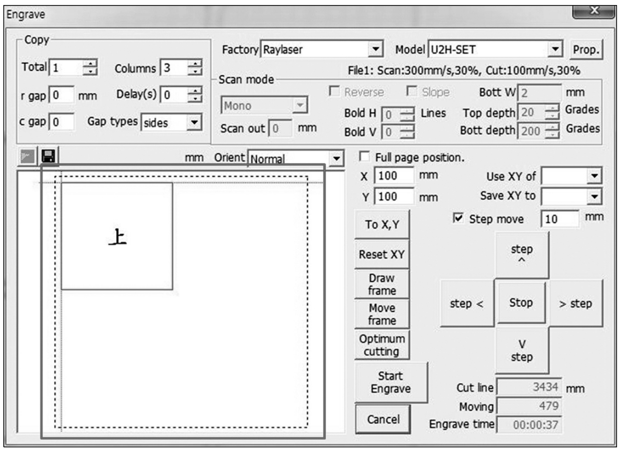

Fig. 4. Setting parameters: the size and the area of the film to be cut.

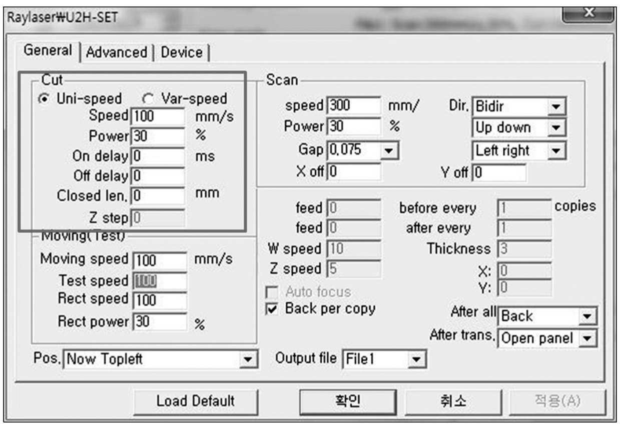

Fig. 6. Setting parameters: laser speed and power, On/Off delay time, and so forth.

gle piece of EBT3 film can be positioned and cut to produce the maximum number of E2E testing films without resulting in wastage. Because laser intensity for cutting was set to relatively low to minimize a film edge damage, film cutting was performed two times at the same location to make the film completely cut off.

3. E2E testing

1) Static tracking mode-6DS mode: A head-and-neck phantom designed for CyberKnife E2E testing was used to examine the items in static tracking mode (Fig. 7). The phantom contains specially designed ball cubes that help position E2E films that are attachable to the ball cubes to serve each test purpose.

A single piece of each A-L and A-S film was used for 6DS mode. Every film was marked with different directions, which were laid orthogonal to each other. It is recommended that direction marking be provided in the corner edge of a film as direction marking in the center may affect the result analysis after film scanning. The orthogonal films were attached to a ball cube located in the head area of the head-and-neck-phantom, which was laid in the proper position for the test before proceeding.

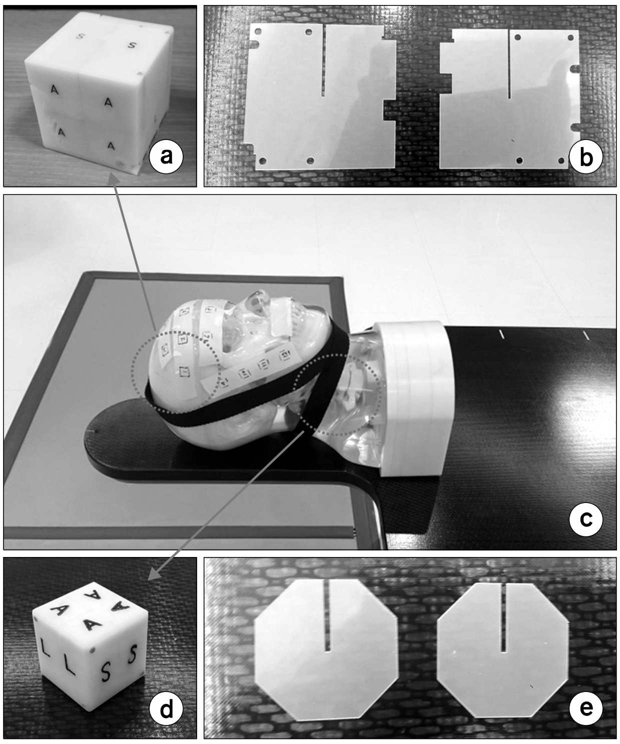

Fig. 7. (a) The ball cube for 6DS tracking mode test. (b) A pair of custom-made films for 6DS tracking mode test. (c) Head-and-Neck phantom used for static tracking modes. (d) The mini ball cube for XS tracking mode test. (e) A pair of custom-made films for XS tracking mode test.

2) Static tracking mode-XS mode: For XS mode testing, two hexagon-shaped XS testing films were placed on a mini ball cube in the cervical spine and arranged such that the films crossed each other. The films were marked with an A-L or A-S direction accordingly and were laid crossing each other on a ball cube that was placed in the cervical spine of the CyberKnife head-and-neck-phantom, which in turn was laid on a couch properly positioned for the test before proceeding.

3) Motion tracking mode-XLT mode: The XLT phantom (CIRS, USA), designed to reproduce lung tumor motion, was used for the motion tracking XLT testing (Fig. 8). A pair of cross-shaped films fabricated for XLT testing were used in this mode. Each film was marked either A-L or A-S, corresponding to its positioning direction, and placed on a cube in a moving rod designed to reproduce respiratory motion. Thereafter, the moving rod was attached to the XLT phantom equipped with a LED platform at the top in order to reproduce

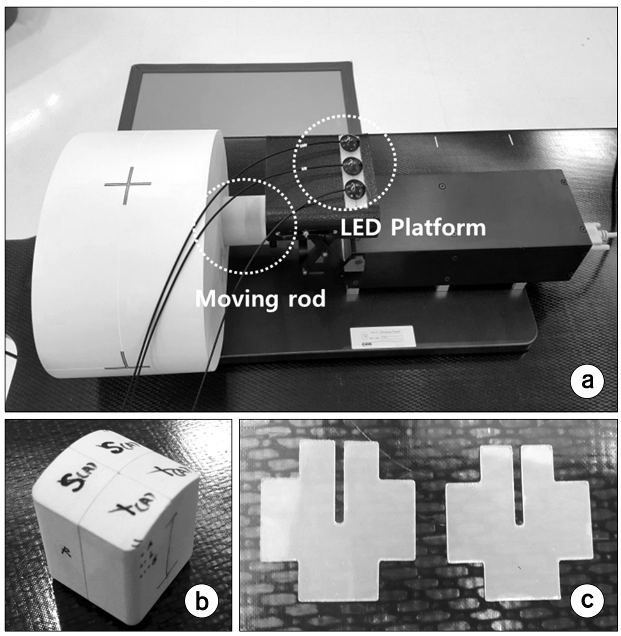

Fig. 8. (a) Xsight Lung Tracking Phantom kit. (b) The film cube located in the moving rod. (c) A pair of custom-made films for XLT mode test.

the respiratory chest movement. This respiratory cycle was sampled to track the lung tumor motion for the testing.

4. Film scanning and result analysis

After the test, the films used for testing were scanned. The A-L and A-S films employed for the testing were scanned with a single piece of non-irradiated film that was positioned at the same column in the scanner for background comparison. The films were scanned at 48-bit color depth and 300 dpi resolution as recommended by the manufacturer (Accuray, USA) and saved in the tiff format. End-to-End film analysis (version 4.0) provided by the manufacturer was used for result analysis.

Results

1. Film fabrication

Unlike the films used in the XLT mode, films for 6DS mode vary in shape depending on whether they are marked in the A-S or A-L direction. Therefore, by using a pair of 8 inch× 10 inch EBT3 films, a sufficient amount of A-S and A-L films, as many as 18 pieces, that are required to conduct up to nine tests could be fabricated. As the films used for XS or XLT tracking mode are identical in shape regardless of direction and are relatively small in size, a total of 40 pieces of E2E films sufficient for 20 tests or less could be fabricated with a single 8 inch×10 inch EBT3 film of each mode. The time needed for film fabrication varies depending on the parameter values set for laser cutter, the maximum number of films in the desired shape, and the extent of shape complexity; approximately five to ten minutes were required to fabricate a single 8 inch×10 inch EBT3 film.

2. E2E testing results

All results are presented by analyzing the errors that were measured from three directions (left, anterior, and superior) and combined into a total targeting error. The differences in the total targeting errors between the original E2E testing film and the film fabricated in this study were 0.17 mm (Table 1) for 6DS mode, 0.3 mm (Table 2) for XLT mode, and 0.17 mm (Table 3) for XS mode. Table 4 summarizes the results of the analysis where the same film was scanned 10 times to examine possible errors associated with incomplete contact between film and scanner surface during film scanning. The standard deviation was 0.012 mm, which indicates that the uncertainty generated by film scanning is relatively low.

Discussion

The currently commercialized films exclusively designed for E2E testing are divided into three types: one for each 6DS tracking, fiducial tracking, and synchrony respiratory modes; one for XS tracking mode; and one for XLT mode. Each type of film pack contains a set of 20 films, and a pair of films will be used for each tracking mode, which in turn allows the films to be tested 10 times. The 8 inch×10 inch EBT3 film used in fabricating a custom-made film for this study is sold in packs of 25 pieces at a price similar to that of the original

Table 1. 6D Skull (6DS) tracking mode: error information.

Error (mm)	Original film	Custom-made film
Left	0.03	−0.12
Anterior (A-L)	0.84	0.15
Superior	0.82	0.89
Anterior (A-S)	0.64	0.41
Average anterior	0.74	0.28
Total targeting	1.11	0.94

Table 2. Xsight Spine (XS) tracking mode: error information.

Error (mm)	Original film	Custom-made film
Left	0.44	0.1
Anterior (A-L)	0.15	−0.14
Superior	0.03	0.15
Anterior (A-S)	0.47	−0.19
Average anterior	0.31	−0.16
Total targeting	0.54	0.24

Table 3. Xsight Lung Tracking (XLT) mode: error information.

Error (mm)	Original film	Custom-made film
Left	−0.37	−0.27
Anterior (A-L)	−0.74	−0.4
Superior	1.03	1.33
Anterior (A-S)	−0.66	−0.75
Average anterior	−0.7	−0.57
Total targeting	1.3	1.47

Table 4. The result of the error information at 6DS tracking mode with custom-made film. Scanning and analysis were performed 10 times, respectively.

Error (mm)	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	Average	Standard deviation
Left	−0.23	−0.16	−0.15	−0.16	−0.16	−0.16	−0.16	−0.16	−0.17	−0.16	−0.17	0.023
Anterior (A-L)	−0.4	−0.38	−0.39	−0.38	−0.37	−0.39	−0.38	−0.38	−0.38	−0.38	−0.38	0.008
Superior	0.27	0.28	0.28	0.29	0.29	0.29	0.28	0.28	0.28	0.27	0.28	0.007
Anterior (A-S)	−0.05	−0.05	−0.04	−0.03	−0.05	−0.04	−0.04	−0.04	−0.04	−0.03	−0.04	0.007
Average anterior	−0.23	−0.21	−0.22	−0.2	−0.21	−0.21	−0.21	−0.21	−0.21	−0.2	−0.21	0.009
Total targeting	0.42	0.39	0.38	0.38	0.39	0.39	0.39	0.39	0.39	0.38	0.39	0.012

E2E film sold in packs of 20 pieces. Therefore, a total of 225 custom-made E2E films for 6DS, fiducial, and synchrony respiratory tracking modes can be prepared by using 25 pieces of 8 inch×10 inch EBT3 films and in the same manner, a total of 1,000 E2E films can be fabricated for XS and XLT tracking modes. Based on this, it can be calculated that a single E2E test using a custom-made film enables the 6DS, fiducial, and synchrony respiratory tracking modes to be tested up to 11 times while allowing the XS and XLT modes to be tested up to 50 times. The custom-made film is also expected to be highly time-efficient owing to its reduced lead time. If films greater than 8 inch×10 inch in size could be placed for cutting, considering the 400 mm×400 mm max working area of the laser cutter used for this study, then it seems possible to fabricate larger amount of E2E films in a single operation of the laser cutter. Therefore, even greater efficiency than the results of this study can be expected in terms of cost reduction.

With concerns about possible thermal damage to cutting plane during film cutting, the parameters optimized for the specific laser cutting system to use for the study, laser aperture, range of available laser intensity, and distance between laser focus and film surface must be determined prior to film fabrication. Laser is replaceable because its intensity decreases with increasing amount of laser consumed. This suggests that it is not desirable to apply the identical parameters to all institutions. Therefore, a preliminary examination must be performed on a laser cutter to serve institution-specific purposes, along with its optimization and maintenance on a regular basis.

Differences in total targeting errors between the commercialized film exclusively designed for E2E testing and the film fabricated in this study may occur due to the potential film setup errors during repeated tests or the inter-observer differences. To minimize such impacts, the same observer was brought in to perform cross measurement, visual inspection of any differences between the original E2E film and the fabricated film prior to the measurement, and verification whether the location remains unaffected after a film was fixed in position. Compared to the original E2E film, the custom-made film for E2E testing was found to be affected by heat generation from the bottom surface during film cutting, which in turn lifts its corner slightly at one specific edge. The custom-made film fabricated as shown in Table 4 was scanned repeatedly 10 times to examine whether such a subtle difference influences the E2E results, which confirms that the uncertainty involved is relatively low. Although this study successfully demonstrates the feasibility of custom-made film for testing purposes, it is still necessary to perform E2E testing multiple times and compare the results to determine whether they are statistically significant. To further ensure accuracy of analysis, the EBT3 film should be positioned in a laser cutter with the entire film surface being in complete contact with the laser cutter's bottom surface, and it needs to be fixed in position before film cutting so as to prevent movement caused by vibrations. In addition, cutting work should be promptly performed so that the potential heat damage from bottom surface can be minimized and more importantly, the setup errors during tests must be minimized.

With a fixed-cone collimator, two items of static tracking mode and a single item of motion tracking mode were selected for E2E testing in this study. Additional E2E tests are needed to include all five items equipped with IRIS and MLC, along with further verification of the test reliability. A comparison will be made to verify that the test using the film fabricated in this study yields the same results as the test using the original film. This verification will also be conducted for other film-based tests such as the MLC alignment and the AQA (auto QA) that has been performed at Yonsei Cancer Center as a daily QA.

Conclusion

Results of the test using E2E exclusive or custom-made film showed that the differences of total targeting error are within 0.3 mm for all three items tested in this study. Given that the tolerance for E2E testing is 0.95 mm, this difference is considered clinically feasible. The results also confirmed that film fabrication can be customized to serve specific testing purposes and further technological advances in custom-made film are expected to increase its economic efficiency.

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