Validation of the Fabricated Cast Nylon Head Phantom for Stereotactic Radiosurgery End-to-End Test using Alanine Dosimeter

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Abstract

Background: Stereotactic radiosurgery (SRS) is an alternative to surgery as it precisely delivers single-large doses to small tumors. Cast nylon is used in phantom due to its computed tomography (CT) number of about 56–95 HU, which is close to that of the soft tissue. Moreover, cast nylon is also more budget-friendly than the commercial phantoms. **Aims:** The aim of this study is to design and validate the fabricated cast nylon head phantom for SRS end-to-end test using an alanine dosimeter. **Materials and Methods:** The phantom was designed using cast nylon. It was initially created by a computer numerical control three-axis vertical machining center. Then, the cast nylon phantom was scanned using a CT simulator. Finally, the validation of the fabricated phantom using alanine dosimeter proficiency with four Varian LINAC machines was performed. **Results:** The fabricated phantom presented a CT number of 85–90 HU. The outcomes of VMAT SRS plans showed percentage dose differences from 0.24 to 1.55, whereas the percentage dose differences in organ at risk (OAR) were 0.09–10.80 due to the low-dose region. The distance between the target (position 2) and the brainstem (position 3) was 0.88 cm. **Conclusions:** Variation in dose for OAR is higher, which might be due to a high-dose gradient in the area where measurement was being conducted. The fabricated cast nylon end-to-end test head phantom had been suitably designed to image and irradiate during an end-to-end test for SRS using an alanine dosimeter.

Keywords: Alanine dosimeter, fabricated cast nylon head phantom, stereotactic radiosurgery

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Introduction

Stereotactic radiosurgery (SRS) is an alternative to surgery with accurate dose delivery of single-large doses to small tumors and using image-guided radiation therapy to check the patient position. This technique irradiates the target to achieve steep dose gradients outside the treatment volume while producing a concentrated dose in the lesion. Approximately 400,000 patients worldwide have been diagnosed with intracranial metastases, where about 70%–80% will have multiple intracranial metastases.[1] SRS's role has recently been expanded to include the treatment of multiple cranial metastases with a single isocenter, resulting in even shorter treatment times. All radiotherapy practices should be subjected to appropriate quality assurance procedures, including regular quality control testing and independent dosimetry audit, to minimize potential errors in treatment delivery that can lead to clinical complications. Meanwhile, the International Atomic Energy Agency (IAEA)[2,3] and the Imaging and Radiation Oncology Core Huston (IROC Houston)[4] are the two largest audit networks. They have conducted extensive studies on the conventional dosimeter in end-to-end tests such as TLD, OSL, and RP glass dosimeter, as well as the standard imaging Lucy 3D, CIRS STEEV phantom,[1] and RUBY phantom[5] in end-to-end test.[6-8] In addition, several studies on SRS have been conducted along with the investigation of anthropomorphic phantoms utilized for complex radiotherapy treatment quality assurance, audits, and trials.[9-12] Since alanine

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has a good response in high dose, it has been reported to benefit a SRS of the intracranial treatment using radiation dose of 15–24 Gy.[13] Furthermore, an alanine dosimeter has been used in high-dose dosimetry to calculate a wide range of radiation doses across various published studies on SRS.[14-17] This study focused on designing and fabrication of cast nylon head phantom, as nylon has a density of 1.14 g/cm^3, and it is robust and transportable to each radiotherapy center. In addition, a cast nylon head phantom is cheaper than a commercial head phantom for SRS.

Materials and Methods

Designing and fabrication of cast nylon head phantom

The phantom was designed using cast nylon because it has a CT number of about 56–95 HU,[18] which is close to that of the soft tissue. The head phantom has a dimension of 15 cm diameter and 17 cm height, drilled for a dosimetry box consisting of four alanine slice pieces each of 1 cm height. The head phantom diameter of 15 cm was selected to represent the diameter of an adult patient's head. This phantom was created by a computer numerical control (CNC) three-axis vertical machining center. Figure 1 shows the design of the fabricated cast nylon end-to-end test head phantom, CNC fabrication parts of the cast nylon, and the completed head phantom.

As displayed in Figure 2b, each alanine slice has 15 holes and each being 1 cm apart from the border and one another. Here, pieces of cast nylon were placed to fill the gap in each hole. Alanine pellets were placed in the holes of the alanine slices and positioned at two measurement points; one in the target volume and another in the organ at risk (OAR) representing the brain stem, where one alanine pellet was used at each measurement position. The dimensions of, both, OAR and target are equal with 5.0 ± 0.1 cm diameter and 2.9 ± 0.1 cm height. Figure 2a shows cross-sectional diagram of the phantom, and [Figure 2b] shows fabricated cast nylon for alanine dosimeter. In addition, the laser mark in this phantom helps align during measurements.

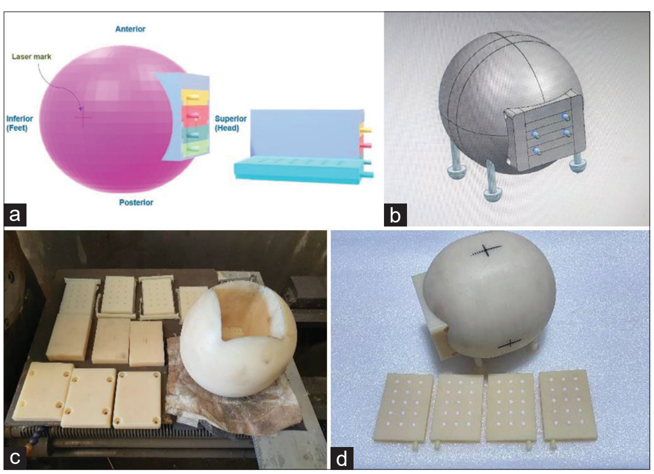

Figure 1: Fabricated cast nylon head phantom: (a) 3D head phantom design, different colors show different parts of phantom component, (b) 3D head phantom design with four feet by CAD, (c) fabricated cast nylon head phantom parts using CNC technique, consist of head drilled sphere for head phantom and alanine box set, and (d) completed set of fabricated cast nylon head phantom. CAD: Computer-aided design, CNC: Computer numerical control

Optimization of dosimeter and electron paramagnetic resonance spectroscopy

The Harwell alanine dosimeter consisted of 90.9% L-alpha-alanine and 9.1% paraffin wax as a binder. These dosimeters were 4.8 ± 0.1 mm in diameter and 2.8 ± 0.1 mm in height, and mass was 60.0 ± 2.0 mg within the overall batch and ± 0.6 mg within a lot (standard deviation of 0.3 mg). This study used alanine batch number BY616. The electron paramagnetic resonance (EPR) spectroscopy (Bruker EMXmicro) is an X-Band machine installed with a standard ER 4119HS resonator (Bruker BioSpin Corporation). The EPR operation parameter was optimized at the radiotherapy level of 1–20 Gy. The acquisition parameters were set as follows: microwave power (MP): 2 mW, modulation amplitude (MA): 7.018 G, time constant (TC): 40.96 ms, center field: 3500 G, sweep width: 200 G, modulation frequency: 100 kHz, sweep time: 40.45 s, receiver gain: 30 dB, and number of scans: 3 times.

Validation of the fabricated cast nylon end-to-end test head phantom

The fabricated head phantom was validated using four Varian 6 MV-FFF linear accelerators consisting of three TrueBeam and one Halcyon. According to RTOG 90-05,[17] the maximum tolerated dose based on tumor size and dose for the lesion is 21–30 mm, where 18 Gy was based on acute and chronic toxicities, but 21 Gy was based on acute toxicity alone.

The fabricated head phantom was scanned using a GE CT simulator (GE HealthCare Chicago, Illinois, USA) with a slice thickness of 1.25 mm. The CT images were imported in the Eclipse (Varian Medical Systems Inc., CA, USA) TPS for contoured target and OAR of 7.9 cm^3 as shown in Figure 3. VMAT-SRS technique was used for 6 MV-FFF photon energy with the plan parameter as listed in Table 1. All simulated plans were optimized with a dose of 18 Gy in a single fraction. The anisotropic analytical algorithm (AAA) was used to calculate the dose, and plans were normalized to deliver 100% of the prescribed dose to 95% of the PTV volume. Later, alanine pellets were placed in the fabricated head phantom and irradiated according to the plan. The plans were analyzed by the cumulative dose-volume histogram (DVH) and tolerance limits as shown in Table 1.

Irradiation setup

Output measurement was performed to ensure the accuracy of the delivered dose from the LINAC, Varian TrueBeam (Varian Medical Systems, Inc., CA, USA). Five alanine dosimeters were irradiated at 10 Gy. The delivery dose was at 10 Gy of 6 MV-FFF. The field size was 10 cm × 10 cm at a depth of D_{max}. The alanine dosimeter was placed between 1 cm of

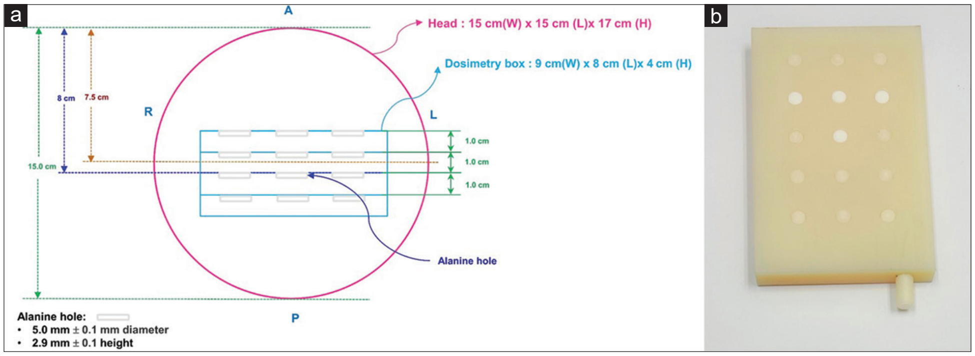

Figure 2: (a) Cross-sectional diagram of the phantom, (b) fabricated slice for alanine dosimeter

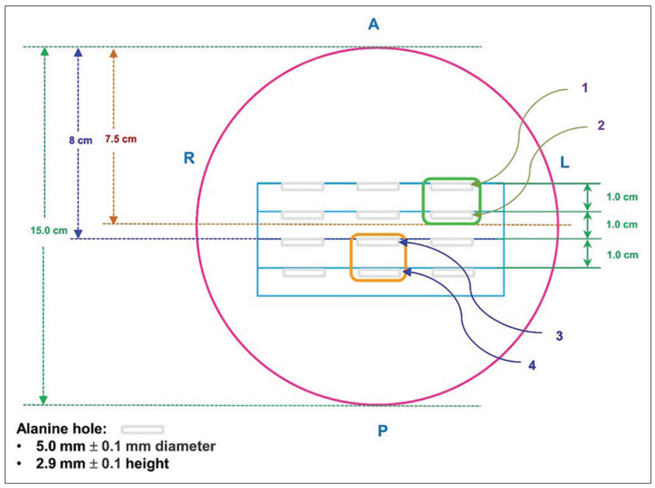

Figure 3: PTV in positions 1 and 2, and the brain stem or OAR in positions 3 and 4. PTV: Planned target volume, OAR: Organs at risk

bolus to reduce the air gap effect in a solid water phantom, as illustrated in Figure 4.

Computed tomography scan simulation

The validation was performed by scanning a set of fabricated phantoms in a CT simulator (GE HealthCare Chicago, Illinois, USA) with a slice thickness of 1.25 mm at 120 kVp as shown in Figure 5.

As shown in Figure 6, the validation of the fabricated cast nylon end-to-end test head phantom was investigated where four pellets of alanine were irradiated in three measurements in each Varian 6 MV-FFF linear accelerator.

Results

Validation of the fabricated cast nylon end-to-end test head phantom

The head phantom was designed and fabricated using cast nylon according to the drawings as illustrated in Figure 1. It was discovered that the phantom has a CT number of approximately 85–90 HU throughout the study. The result shows that no artifacts were found and no significant difference of dimensions between the phantom and the planned [Figure 7].

Table 1: Plan parameter

Parameter	Setting
Treatment technique	VMAT
Photon energy	6 MV-FFF
Prescribed dose (PTV)	18 Gy
Tolerance dose limits	
Brain stem (OAR)	$D_{0.1\ cc}$ <8 Gy

PTV: Planned target volume, OAR: Organ at risk, VMAT: Volumetric modulated arc therapy, MV-FFF: MV flattening filter free

The results of VMAT SRS plans are listed in Table 2. Here, the results indicate that the target percentage difference ranges from 0.24 to 1.55 for the fabricated cast nylon end-to-end test head phantom for TrueBeam and Halcyon. Even though the percentage difference range in the OAR was larger, ranging from 0.09 to 10.80 for TrueBeam and Halcyon.

Uncertainty budget

Table 3 presents the uncertainty of end-to-end test. The uncertainty number 1–7 is the characteristics of alanine came from the previous in-house study. The characteristic consists of uniformity, reproducibility, linearity, repetition rate, energy dependence, directional dependence, and fading. The standard

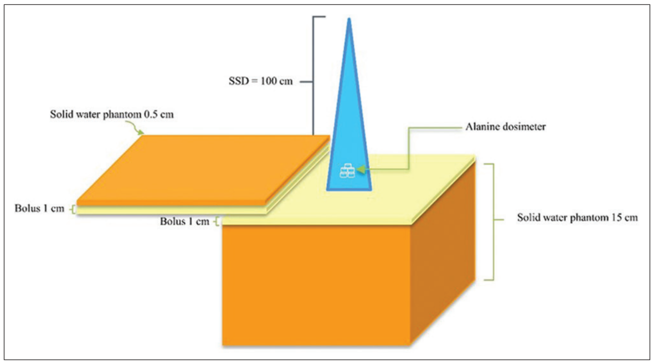

Figure 4: Irradiation setup of alanine dosimeter at 10 Gy

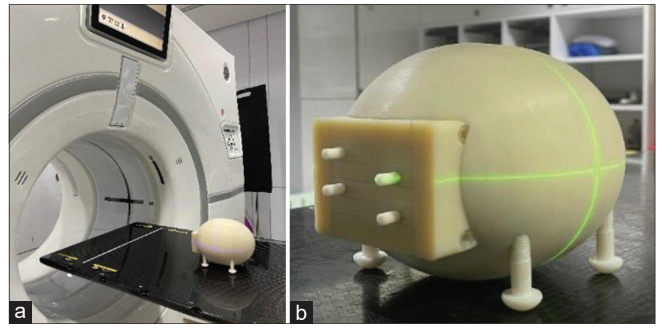

Figure 5: Characterization of fabricated cast nylon head phantom using CT simulator (a) phantom setting and (b) phantom alignment. CT: Computed tomography

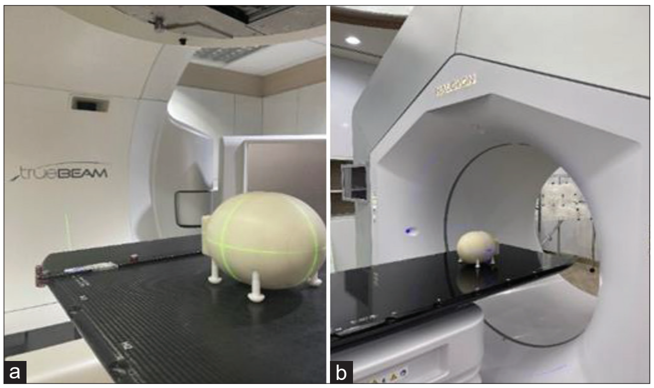

Figure 6: Irradiation of fabricated head phantom with a set of alanine dosimeters inside using TrueBeam (a) and Halcyon (b) with 6 MV-FFF LINAC

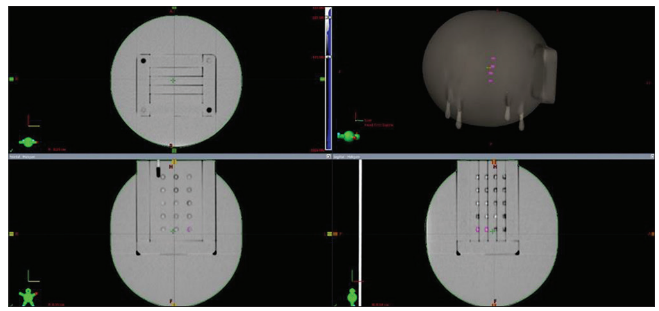

Figure 7: CT images of the fabricated head phantom. CT: Computed tomography

output uncertainty was calculated from the mechanical QA process. The uncertainty of ionization chamber calibration was reported at the 1% for absorbed dose to water with can be traced to SSDL Thailand. Overall, the expanded uncertainty of measurement was estimated 2.8% at 95% confidence interval ($k = 2$).

Discussion

As illustrated in Figure 7, the fabricated cast nylon end-to-end test head phantom was presented as a homogeneous material with no artifacts and a CT number about 85–90 HU.

As shown in Table 1, the target percentage dose difference for the fabricated cast nylon end-to-end test head phantom for TrueBeam and Halcyon ranges from 0.24 to 1.55. Even though the percentage difference in OAR for TrueBeam and Halcyon ranged from 0.09 to 10.80. Dimitriadis *et al.* have shown the results of 18.76% with 1.2% agreement between plastic scintillation detector and one pellet alanine in the OAR.[6]

Since the measurement was conducted in an area with a high dose gradient, the distance between the target (position 2) and brainstem (position 3) was 0.88 cm [Figure 8], this is the distance between planning target volume (PTV) and OAR, or position 2 and position 3, which is the closest distance between PTV and point of measurement in OAR. The differences between treatment planning system (TPS) calculated doses are larger in the OAR than in the target, during which a small positional deviation results in a large dose difference.

Table 2: Validation of the fabricated cast nylon end-to-end test head phantom (percentage difference=(D_{TPS}-$D_{alanine}$)/$D_{alanine}$ ×100)

Machine	Position	TPS (Gy)	Alanine (Gy), mean±U_c	Percentage difference
True beam 1	1	18.91	18.96±2.2	−0.24
	2	18.80	18.87±2.2	−0.38
	3	1.81	1.96±2.2	−7.44
	4	1.31	1.35±2.2	−3.16
True beam 2	1	18.91	19.06±2.2	−0.76
	2	18.80	19.01±2.2	−1.11
	3	1.81	1.98±2.2	−8.22
	4	1.31	1.29±2.2	1.45
True beam 3	1	18.91	19.19±2.2	−1.47
	2	18.80	18.97±2.2	−0.90
	3	1.81	1.88±2.2	−3.29
	4	1.31	1.31±2.2	−0.09
Halcyon	1	18.79	18.86±2.2	−0.40
	2	18.89	19.18±2.2	−1.55
	3	1.41	1.58±2.2	−10.80
	4	0.81	0.78±2.2	4.36

TPS: Treatment planning system

Table 3: Uncertainty of alanine following "Guide to the expression of uncertainty in measurement"[19]

Number	Source of uncertainty	Type	Relative standard uncertainty (%)
1	Uniformity of alanine dosimeter	A	0.4
2	Reproducibility of alanine dosimeter	A	0.1
3	Linearity of alanine dosimeter	A	0.4
4	Repetition rate of alanine dosimeter	A	0.2
5	Energy dependence of alanine dosimeter	A	0.2
6	Directional of alanine dosimeter	A	0.1
7	Fading of alanine dosimeter	A	0.4
8	Standard output	B	0.5
9	N_{Dw} calibration of the user dosimeter at the standard laboratory	B	1.0
Combined uncertainty (Uc)			1.4
Coverage factor (k)			2.0
Expanded uncertainty			2.8

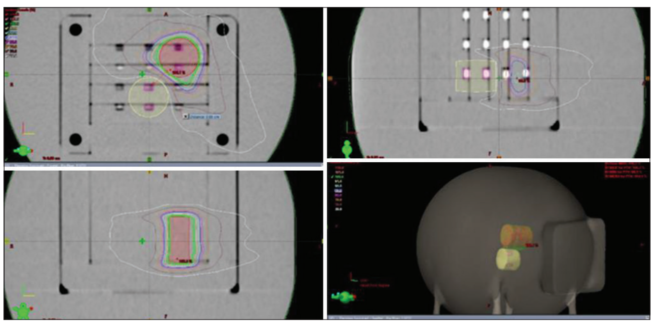

Figure 8: Fabricated head phantom isodose distribution in axial, coronal, sagittal, and 3D view from VMAT

Conclusions

This study presented the creation of a novel fabricated cast nylon end-to-end test head phantom suitably designed to image and irradiate during an end-to-end test for SRS using alanine dosimeter. Moreover, this fabricated cast nylon head phantom is a multipurpose tool and budget-friendly for the dosimetric verification of radiotherapy treatment planning systems that shall benefit various radiotherapy institutes.

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Conflicts of interest

There are no conflicts of interest.

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