Original Article

Design, Fabrication, and Validation of a Polymethyl Methacrylate Head Phantom for Dosimetric Verification of Cranial Radiotherapy Treatment Plans

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Abstract

Purpose: The present study aims to design and fabricate a novel, versatile, and cost-effective Polymethyl Methacrylate (PMMA) head phantom for the dosimetric pretreatment verification of radiotherapy (RT) treatment plans. **Materials and Methods:** The head phantom designing involves slice-wise modeling of an adult head using PMMA. The phantom has provisions to hold detectors such as ionization chambers of different sizes, Gafchromic films, gel dosimeter, and optically stimulated luminescence dosimeter. For the point dose verification purpose, 15 volumetric modulated arc therapy patient plans were selected, and doses were measured using a CC13 ionization chamber. The percentage gamma passing rate was calculated for acceptance criteria 3%/3 mm and 2%/2 mm using OmniPro I'mRT film QA software, and Gafchromic EBT3 films were used for 2D planar dose verification. **Results:** Treatment planning system calculated, and the measured point doses showed a percentage deviation ranged from 0.26 to 1.92. The planar dose fluence measurements, for set acceptance criteria of 3%/3 mm and 2%/2 mm, percentages of points having gamma value <1 were in the range of 99.17 ± 0.25 to 99.88 ± 0.15 and 93.16 ± 0.38 to 98.89 ± 0.23, respectively. Measured dose verification indices were within the acceptable limit. **Conclusions:** The dosimetric study reveals that head phantom can be used for routine pretreatment verification for the cranial RT, especially for stereotactic radiosurgery/RT as a part of patient-specific quality assurance. The presently fabricated and validated phantom is novel, versatile, and cost-effective, and many institutes can afford it.

Keywords: Gamma analysis, head phantom, point dose

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Introduction

External beam radiation therapy is among the most commonly used treatments for various tumors. Advances in radiation therapy have resulted in dose escalation and also a better precision during treatment. Due to the complex nature of the advanced treatment technique using multi-leaf collimators (MLCs), pretreatment verification is an important aspect of the quality assurance (QA) program.[1,2] Although most treatments are performed accurately, accidents have been reported even in centers with advanced technology and experienced staff.[3,4] Therefore, patient-specific QA (PSQA) is an essential step to ascertain that the equipment is capable of delivering the plan generated in the treatment planning system (TPS) within the acceptable tolerances.[5-8] PSQA facilitate the clinical implementation of intensity-modulated radiotherapy (RT) delivered using MLCs. PSQA involves measuring the point dose and analyzing the planar dose distribution from the TPS on a water-equivalent phantom material before treating a patient.

A number of verification phantoms are available commercially with different types of detectors for advanced RT techniques.[9-12] A majority of these phantoms are made up of solid/plastic water materials, and most of them are not suitable for QA of cranial RT. Although a few phantoms are suitable like Lucy three-dimensional (3D) stereotactic radiosurgery/RT (SRS/SRT)

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QA phantom[13] from Standard Imaging Inc. (Middleton, WI, USA), they are very expensive (unaffordable to many centers) and some have limited measurement options especially for SRS/SRT QA. Therefore, there is a need for a low-cost QA head phantom with tissue equivalent materials, which is suitable for dosimetry QA of cranial RT using advanced RT techniques. Although the dosimetry protocols recommend performing the measurements in water, solid water substitutes are widely used because of their convenience and satisfactory results.[14,15] For maintaining accuracy and precision in QA procedure, the physical and radiological properties of water and the phantom material should be equivalent.[16,17]

In this work, the effort is taken to design and fabricate a protruding type novel head phantom that can contribute to PSQA with actual treatment parameters of a plan with noncoplanar beams. As an initial step, we fabricate the phantom with Polymethyl Methacrylate (PMMA) $(C_5O_2H_8)_n$ as it is cheap and easily available. Article describes the head phantom design, fabrication, and also the steps involved in its validation and results.

Materials and Methods

Head phantom design and fabrication

The phantom was designed using PMMA slabs. Commercially available PMMA slabs have a thickness ranging 10–40 mm were used. The slabs were stacked together and machined such that the external contour of the slabs matches that of an average human head with an inter-pterion distance of 14.5 cm. The average human head dimension was acquired for fabricating the phantom from the computed tomography (CT) data set of head available in our hospital. The model was sectioned in the craniocaudal direction. The inner dimensions of the PMMA slabs were tooled using a 3D Computer Numerical Control (CNC) router (Makino S56), a five-axis vertical machining centre with a spindle speed of 13,000 rpm. Figure 1 shows the phantom design, the machining process, the finished product, and the assembled phantom on the treatment couch for dose measurements. Carefully, the point of measurement was kept at the interface of two selected slices for all the detectors. This will help in identifying the plane to align the phantom using lasers during measurements. To conveniently handle and properly fix the slices, tongue and groove joints were provided on both sides of the slices. Figure 2 shows a slice drawing and the corresponding machined part. The external contour was later machined, stacking the individual slices. In addition, two PMMA cylindrical rods with 2 cm diameter were provided to secure the slices while the phantom is on the treatment couch.

A cavity of size 40 mm × 40 mm × 40 mm was provided in the region of dose measurements for positioning the different dosimetric detectors such as ionization chambers with various active volumes, gel dosimeter, radio-chromic films and optically stimulated luminescence dosimeter (OSLD). Due to the constraints in the machining of internal dimensions, cavity fillets (cuboids) were provided at the internal vertical edges of the cavity. The cuboid inserts for various types of detectors were modeled with Creo Parametric, a 3D modeling software after physical measurements, and applying required tolerances and were machined individually on the CNC router. The cuboid inserts were machined in symmetric halves owing to the small tolerances applied, which would be subsequently glued together. The point of measurement for all detectors was positioned at the center of the cuboid. Figure 3 shows the drawing of 40 mm × 40 mm × 40 mm cuboid with a detector holder and the corresponding machined part.

Provisions for placing Gafchromic film and gel dosimeter were also included in the design. Figure 4a and b shows the schematic diagram for the gel and film inserts of

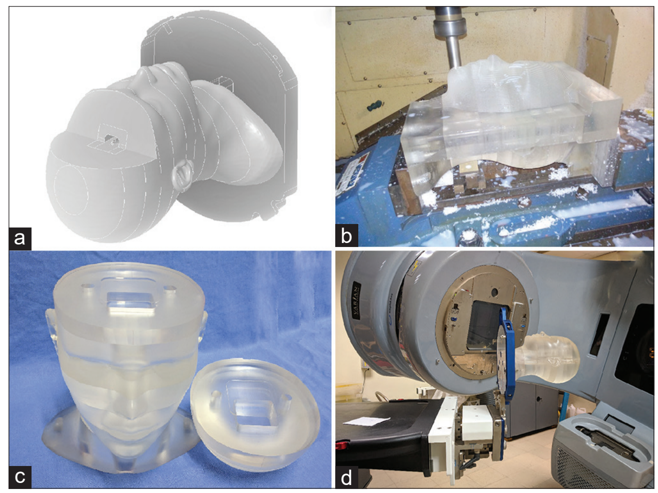

Figure 1: Head phantom concept to reality: (a) designed part (b) machining the outer contour of the phantom using a Computer numerical control machine (c) fabricated head phantom, and (d) phantom mounted on linear accelerator couch for dose measurements

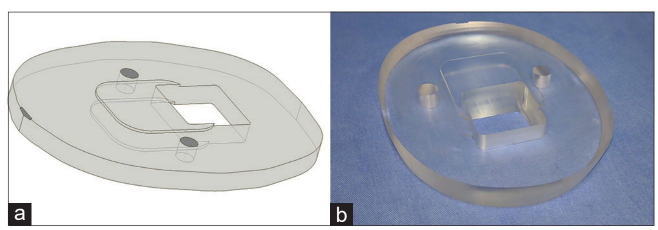

Figure 2: (a) Individually designed slice three dimensional model and (b) the corresponding machined part

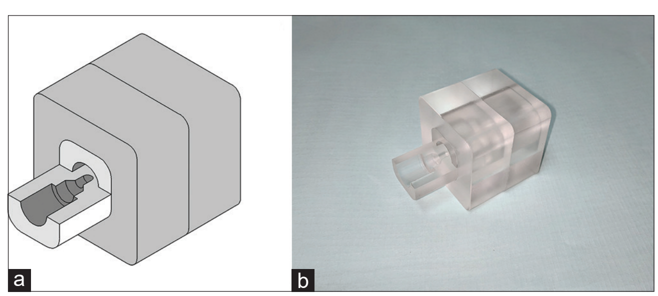

Figure 3: (a) 40 mm× 40 mm × 40 mm cuboid three dimensional model with detector insert and (b) the corresponding machined part

40 mm × 40 mm × 40 mm. Figure 4c shows the fabricated OSLD insert. Gel and OSLD inserts are intended for the future dosimetric works. Care was taken to align the point of measurement of the detectors at the center of the cuboid. The head phantom was mounted on the treatment couch using BrainLab® Stereotactic Frame Interface (BSFI) through a base plate machined out of PMMA. The base plate closely followed the inner contour of the BSFI frame. Slots were provided on this plate for the inserts.

Validation of the phantom

Point dose measurements

For this purpose, CC13 (IBA Dosimetry, Active volume 0.13 cc) ionization chamber with their holders was placed in the head phantom for evaluating the treatment plans. In our institute, CC13 ionization chamber is routinely used for the point dose measurements. CT set of the phantom with detector was taken in CT simulator (GE Optima [580W], GE Healthcare) with a slice thickness of 1.25 mm. These CT sets were imported in the Eclipse V13.7.14 (Varian Medical Systems, Palo Alto, CA, USA) TPS for creating the treatment verification plans. Figure 5 shows the sagittal view of the head phantom with a CC13 detector placed at the isocenter. Volumetric-modulated arc therapy (VMAT) verification plans of 15 patients were created with co-planar arcs. The verification plans were delivered on the head phantom in Varian Clinac iX 6 MV Medical Linear Accelerator.

Planar dose verification

As a part of PSQA, unaltered fluence of the verification plan was analyzed using-EBT3 film (Ashland, NJ, USA). For this purpose, we have selected SRT verification VMAT plans of 5 patients with field size <40 mm × 40 mm. The SRT VMAT plans include co-planar arcs (a combination of full and partial arcs) with a prescribed dose of 3.5 Gy delivered for the QA purpose. A precut 40 mm × 40 mm Gafchromic EBT3 film was placed axially at the isocentric plane that was irradiated with respective verification plans, as shown in Figure 6a. The irradiated films were scanned by a flatbed scanner (EPSON® Expression 10000XL; EPSON, UK), and the images are saved in RGB uncompressed tagged image file format, as shown in Figure 6b. Two-dimensional dosimetric analyses of films were carried out using OmniPro I'mRT (Scanditronix Wellhofer AB, Sweden) film QA software by comparing it with the unaltered planar dose pattern from TPS. To obtain the calibration curve for the External Beam Therapy (EBT) films, a set of 50 mm × 30 mm EBT3 film samples was placed perpendicular to the beam direction in a PMMA slab phantom and irradiated with 6 MV X-rays with known doses of 0, 50, 100, 150, 200, 250, 350, 450, 550, 600, and 650 cGy. A dose-response curve was plotted, and the best fit of these data was used to determine unknown dose values from the knowledge of OD of exposed films using the polynomial equation.[17]

$$\text{Dose} = a \times OD + b \times OD^{c}$$

Where a, b, and c are the fitting parameters.

Results and Discussion

The head phantom was designed and fabricated as per the drawings. The phantom setup found to be user friendly and firmly withstand in the cantilever position for the dose

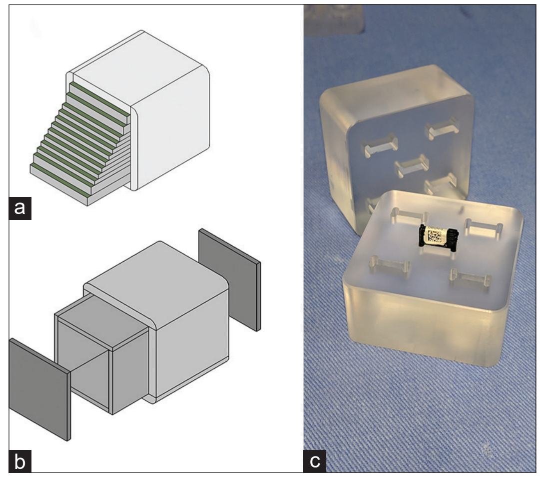

Figure 4: Cavity insert drawing with external dimension 40 mm × 40 mm × 40 mm for (a) Gel dosimetry (b) radio-chromic film and (c) fabricated optically stimulated luminescence dosimeter insert cuboid

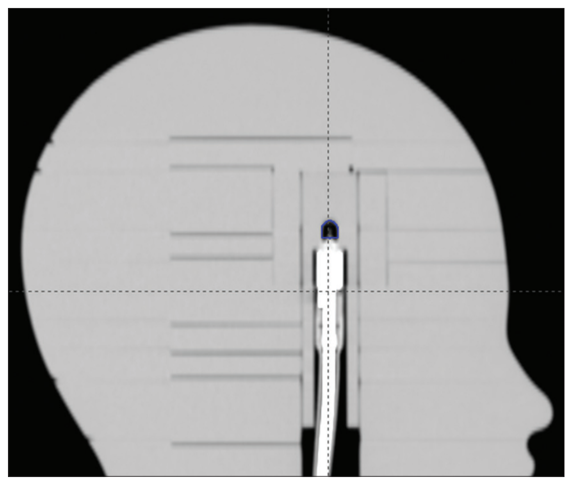

Figure 5: Sagittal computed tomography view of the head phantom with detector CC13

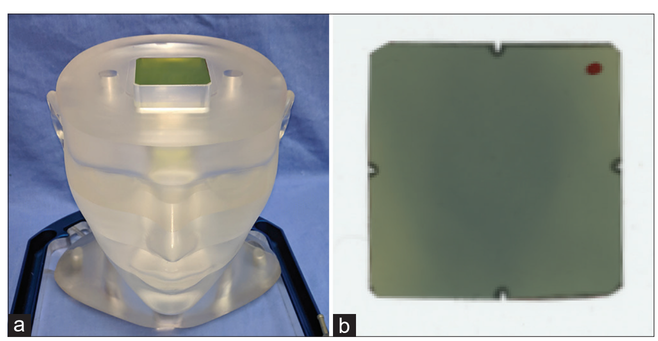

Figure 6: (a) 40 mm × 40 mm Gafchromic EBT3 film placed in the phantom for irradiation and (b) the exposed film with fiducial marks on the films

measurements. Moreover, SRS/SRT QA setups demand such phantoms. The cost of the head phantom is found to be about 6 to 8 times lesser than the cost of Lucy 3D SRS/SRT QA phantom and similar other commercial phantoms with equivalent features. This helps to make it affordable to many institutes. The results of VMAT verification plans of 15 patients are tabulated in Table 1. The table indicates that the relative percentage variation ranges from 0.26 to 1.92 for the head phantom. The mean percentage of deviation of 0.87% was found.

Figure 7 shows the planar dose analysis using the Gafchromic EBT3 film in the transverse plane through the isocenter of the head phantom. The gamma analysis results reveal that for set acceptance criteria of dose difference (3%) and distance to agreement (3 mm); percentages of points having gamma value <1 were in the range of 99.17 ± 0.25 to 99.88 ± 0.15 while for a set acceptance criterion of 2% and 2 mm; percentages of points having gamma value <1 were in the range of 93.16 ± 0.38 to 98.89 ± 0.23, as shown in Table 2. During the gamma analysis, threshold dose was set to 10% of isocenter dose.

Fabricated head phantom can improve the PSQA procedures, especially for SRS/SRT techniques that need more degrees of freedom during beam delivery. Most of the RT centers use slab phantoms or other expensive commercially available phantoms such as ArcCheck phantom (Sun Nuclear Corporation, Melbourne, FL, USA), Octavius phantom (PTW®-Freiburg, Germany), etc., for the PSQA of SRS/SRT plans. It is typically placed over the couch and difficult to simulate the actual treatment positions while doing QA. Thus it fails to simulate noncoplanar treatment positions. The present head phantom can be used for the collision checks of the gantry and couch prior to the complex non-coplanar beam treatment delivery. The fabricated head phantom holds all the detectors in such a way that the point of measurement of each detector remains the same. This allows the phantom setup easier. In the present phantom, all the ionization chamber detectors are inserted through the rear side of the phantom. This avoids the chamber connector cables from radiations as it may create noise in the signals. The design can overcome the surface irregularity

Table 1: Validation results of the head phantom using a CC13 ion chamber

Point dose measurements using a CC13 ion chamber for VMAT plans			
Number of patients	**TPS dose (cGy)**	**Measured dose (cGy)**	**Percentage of variation**
1	180.90	183.86	1.61
2	190.70	194.43	1.92
3	186.50	187.14	0.34
4	178.40	178.87	0.26
5	181.40	182.32	0.50
6	188.40	192.03	1.89
7	178.50	179.94	0.80
8	190.00	191.11	0.58
9	172.40	173.87	0.85
10	196.20	197.60	0.71
11	187.30	188.74	0.76
12	184.10	184.90	0.43
13	177.40	179.81	1.34
14	177.70	178.33	0.35
15	186.40	187.67	0.68
Mean percentage of deviation			0.87

VMAT: Volumetric Modulated Arc Therapy, TPS: Treatment Planning System

Table 2: Gamma analysis statistics of stereotactic radiotherapy patients in the transverse plane

Serial number of patients	**Gamma Analysis (DTA, DD)**	
	3 mm/3% (SD)	**2 mm/2% (SD)**
1	99.88±0.15	98.89±0.23
2	99.17±0.25	93.16±0.38
3	99.73±0.18	96.50±0.27
4	99.81±0.19	95.38±0.28
5	99.85±0.16	96.23±0.24

SD: Standard deviation, DD: Dose difference, DTA: Distance to agreement

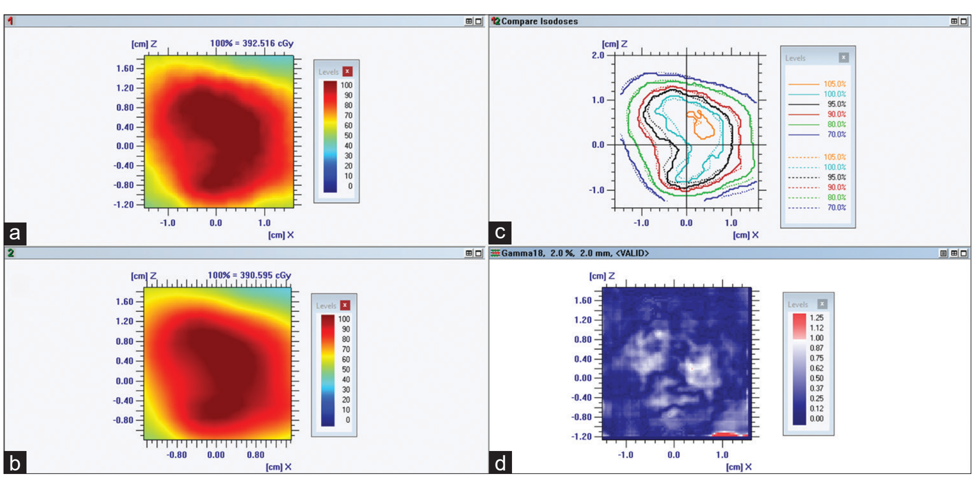

Figure 7: (a) Transverse plane film image, (b) Transverse unaltered planar dose, (c) combined isodose lines and (d) the corresponding gamma analysis

and couch attenuation factor while performing the PSQA compared to commercially available phantoms. This phantom can also be used to measure the dose to the body surface of the critical organs such as lens, thyroid using appropriate surface dosimetry detectors. Phantom measurement results are in better agreement with the TPS calculated values. The dosimetric study results show that the designed head phantom can be used for the routine pretreatment verification for the cranial RT.

Conclusions

A novel, versatile, cost-effective PMMA head phantom was designed, fabricated validated for the PSQA. Developed head phantom can be used for routine pretreatment verification for the cranial RT, especially for SRS/SRT as a part of PSQA.

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Conflicts of interest

There are no conflicts of interest.

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