RSC: A 3D printed eyeball phantom for Sr-90 dosimetry measurements

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Abstract. Strontium 90 (Sr-90) has been commonly used in the radiation treatment of pterygia of the eye. A radioactive plaque is placed in an applicator onto the surface of the eyeball for a specific length of time to achieve a desired dose. Dose is usually calculated using source activity and decay, as well as the distance from it to the surface of the eye. However, this assumes a flat eye surface. This investigation used 3D printing to produce an anthropomorphic eyeball phantom on which to perform dosimetry measurements for two different applicator sizes. These doses were compared to planar geometry measurements and a dose difference found. While planar geometry measurements are useful for routine quality assurance, measurements of the effects of the curved surface on dose calculations can provide valuable clinical information.

1. Introduction

Strontium 90 (Sr-90) is a valuable tool for radiation treatment of pterygia due to the short range of beta particles it emits. Pterygia is a benign growth that occurs on the surface of the eye. Commonly used post-surgery, the treatment is an effective method to help prevent recurrence of the condition. It involves the use of a radioactive plaque placed in an applicator on the eyeball for a specific length of time to achieve the desired dose [1]. The dose can be calculated using simple estimates based on source activity and the distance from it to the surface of the eye, dependent on the applicator. Sr-90 has a half-thickness of 1.5 mm, meaning after 1.5 mm penetration through water, the dose rate is attenuated by 50%, making it ideal for use with surface therapy [2].

A number of studies exist on the calibration of Sr-90 sources using a variety of dosimeters [3-5]. The ICRU report 72 provides guidelines for the dosimetry of beta rays for brachytherapy with sealed sources [6]. The 2015 paper by Laoues et al [7] simulated a Sr-90 treatment using Monte Carlo calculations and compared this to physical measurements performed with film. A good agreement was found between the film measurements and the Monte Carlo results; however, these doses were higher than that provided by the manufacturer. No investigations found in the literature however, have performed measurements on an anthropomorphic eyeball model that allows the curvature of the surface of the eye to be taken into account.

This study therefore used medical imaging data to design an eyeball with anatomically realistic geometry and density, which was fabricated using 3D printing and used to perform film dosimetry measurements of Sr-90 treatments using two applicators of different aperture sizes.
2. Method

2.1. Fabricating the eyeball phantom

MRI datasets of 13 healthy volunteers were used to take dimensions of 26 eyeballs. The collection of this MRI data for use in radiotherapy phantom design was approved by the Metro North Hospital and Health Service Human Research Ethics Committee. Each eyeball was measured in the transverse, sagittal and axial planes. The dimensions for each lens were also recorded. These dimensions were used to obtain an average eyeball size.

The HU values of the different structures of the eye were taken from CT datasets. An average HU value of approximately +1 was found for the vitreous humour of the eyeball and a value of +33 was obtained for that of the lens. Due to the relatively small difference between the vitreous humour and lens densities, it was decided not to include the lens in the print as the uncertainty in the density of the printed material outweighed the difference.

An average eyeball model was designed using Tinkercad (Autodesk Inc., San Rafael, USA). Initially, an eyeball was contoured in MIM Maestro ver. 6.7.6 (MIM software Inc, Cleveland, USA) on one of the MRI datasets and an STL of the volume exported. This was then scaled to match the average dimensions calculated. However, it was found that the voxelisation from the CT images meant the model was not smooth or an accurate shape. Instead, the average dimensions were used to scale and shape a simple sphere in Tinkercad, to achieve the required eyeball shape. This was then sliced into quarters for film planes and 3D printed in PLA with 86% infill using a Raise 3D (Raise 3D Technologies, Irvine, USA) Pro 2 FDM 3D printer, in polylactic acid (PLA). A holder to support the eyeball and provide scatter was also printed using PLA. The eyeball, in position in the holder, was CT-scanned and analysed for any inconsistencies in the print using in-house 3D print QA software [8].

2.2. Dosimetry measurements

Radiochromic film was used for the dosimetry of the two Sr-90 applicators, with respective aperture diameters of 1.6 and 1.0 cm, while the Sr-90 source had an active diameter of 1.1 cm. Film was prepared as per recommended methods, including pre-irradiation scans [9]. Two calibrations were performed using a 6 MV beam and a 300 kVp beam with ten pieces of film irradiated with doses of 0 – 400 cGy for each. The effective energies were interpolated between to derive a calibration curve for Sr-90.

Two measurement setups were used for each applicator, one with the film in the vertical cross section of the 3D printed eyeball model (Figure 1) and one with film on the surface of a stack of virtual water for a planar geometry (Figure 2). Two pieces of film were irradiated for each applicator, with each film being irradiated for 1 minute.

![Figure 1. Set up of eyeball phantom and film with Sr-90 source and applicator](image)
Approximately 48 hours after irradiation, each piece of irradiated film was scanned with the same setup as the pre-irradiation scans to allow pixel values to be converted to dose using the derived calibration relationship, according to an established film analysis method [9, 10].

Dose images were calculated, and the dose distributions were analysed for each applicator and the planar geometry measurements. Multiple line plots across the vertical plane were used to measure the dose in the vertical plane, perpendicular to the source, for each applicator film measurement.

As the edges of the film were observed to be affected by delamination despite careful cutting with scissors [11], doses measured in the eyeball phantom for each applicator were compared at a depth of 0.15 cm, where the dose was unaffected by delamination on all films, rather than at the surface, which would have been ideal.

3. Results

3.1 The eyeball phantom
The average diameters of the eyeballs analysed from the MRI datasets and used for the eyeball phantom design were 24.51 ± 0.02 mm, 24.63 ± 0.02 mm and 25.17 ± 0.02 mm in the sagittal, transverse and vertical directions, respectively. These dimensions agree with the mean eyeball diameters given in ICRP “Report of the task group on reference man” [11]. The printed model and the QA results can be seen in Figure 3.
3.2 Dosimetry measurements

The dose to the surface of the eye was calculated using the calibration certificate of the source, the decay of Sr-90 and a calculated standoff factor (account for the distance between the source and the eye due to the applicator design) for each applicator. These calculated doses, as well as the measured doses for each setup are presented in Table 1.

| Applicator diameter | Applicator standoff | Calculated dose (Gy/min) | Measured planar dose at surface (Gy/min) | Measured eyeball dose at 0.15 cm depth (Gy/min) |
|---------------------|---------------------|--------------------------|------------------------------------------|-----------------------------------------------|
| 1.6 cm              | 0.8 cm              | 1.9                      | 1.9 ± 0.2                                | 1.6 ± 0.1                                     |
| 1.0 cm              | 0.6 cm              | 3.4                      | 3.7 ± 0.4                                | 2.8 ± 0.1                                     |

4. Discussion

The results shown in Table 1 indicate that the measured dose from the planar set up was in agreement with the calculated dose. This result is unsurprising, given that the dose calculation assumes a flat eyeball. While the literature suggests that at a depth of 0.15 cm the dose should be 50% of the maximum, the measurements performed on the eyeball phantom give a dose approximately 80% of the surface dose from the planar setup. This would be due to the curvature of the eyeball surface, which brings the treated tissue closer to the source than the applicator standoff distance, and is a more realistic approximate of what a patient would receive at this depth during a treatment. It would have been ideal to measure the dose at the surface of the eyeball phantom, but delamination is a common issue encountered in film dosimetry [12].

It is therefore advisable to use planar measurements (such as shown in Figure 2) for any routine quality assurance of the Sr-90 source, but as there is a difference between measurements performed on a flat set up and those done on an anthropomorphic phantom, the 3D printing of an eyeball phantom can help give a more realistic indication of the dose received by a patient undergoing this treatment. The methods used in this work can also be used by other radiotherapy centres performing ocular treatments with Sr-90, or other sources, to print 3D models and perform dosimetry with local applicator systems, to test the assumptions underlying treatment dose calculations.

5. Conclusion

A 3D printed eyeball phantom was printed and used with radiochromic film to investigate the difference in dose between planar geometry and a more realistic dose the patient would receive when being treated with Sr-90 for pterygia. The planar geometry measurements agreed with simple dose calculations for the source used, while the eyeball measurements at a depth of 0.15 cm gave a higher dose relative to the planar surface dose at this depth due to the curved eyeball surface.

While simple, planar phantoms are useful for routine quality assurance, 3D printed anthropomorphic phantoms can provide important additional information regarding the doses delivered to more complex human anatomy.

6. References

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