3D polymer gel dosimetry and Geant4 Monte Carlo characterization of novel needle based X-ray source

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Abstract. In the recent years, there have been a few attempts to develop a low energy x-ray radiation sources alternative to conventional radioisotopes used in brachytherapy. So far, all efforts have been centered around the intent to design an interstitial miniaturized x-ray tube. Though direct irradiation of tumors looks very promising, the known insertable miniature x-ray tubes have many limitations: (a) difficulties with focusing and steering the electron beam to the target; (b) necessity to cool the target to increase x-ray production efficiency; (c) impracticability to reduce the diameter of the miniaturized x-ray tube below 4 mm (the requirement to decrease the diameter of the x-ray tube and the need to have a cooling system for the target have are mutually exclusive); (c) significant limitations in changing shape and energy of the emitted radiation. The specific aim of this study is to demonstrate the feasibility of a new concept for an insertable low-energy needle x-ray device based on simulation with Geant4 Monte Carlo code and to measure the dose rate distribution for low energy (17.5 keV) x-ray radiation with the 3D polymer gel dosimetry.

1. Basic conception and general description of the X-ray system

The essence of the offered concept [1, 2] is a two-stage production of x-ray radiation as shown in figure 1. First, a primary x-ray beam is generated by a conventional x-ray tube and guided into a hollow needle through an optical collimator. Then, the collimated x-ray beam excites a metal target installed inside the needle and causes the target to emit x-ray fluorescence that is mainly defined by the characteristic lines of the target material and parameters of the incident x-ray beam. The target can be implemented in different geometries and arrangements. That makes the needle with a built-in target a miniaturized source of radiation potentially applicable to treatment of tumors. If the needle is inserted into the tumor, the produced by the target x-ray fluorescence expands through the needle walls and can be used as a treatment beam irradiating the tumor from the inside out.
2. Monte Carlo simulations
The simulations were done using Geant package version 4.8.1.p02 with low energy data pack G4EMLOW version 4.0 which includes data from EPDL97 (Evaluated Photon Data Library from Livermore). This library is among the recommended by the AAPM (American Association of Physicists in Medicine) in TG-43U1 protocol [3]. Dose rate calculations were done in two simulation steps. First, a set of photon energies comprising the tube spectrum was obtained. Second, photons with these energies were directed onto a secondary target and spatial distribution of deposited dose was accumulated.

Four different configurations have been simulated: cone or wedge shaped secondary target made of either Molybdenum or Copper. Table 1 summarises maximal dose rates as a function of distance from needle axis within vertical longitudinal plane. Figure 3 shows constant dose rate contours within vertical longitudinal plane (Z = 0, see coordinate system layout at figure 2).

| R (mm) | Mo-cone | Mo-wedge | Cu-cone | Cu-wedge |
|--------|---------|----------|---------|----------|
| 5.25   | 1598    | 2143     | 2782    | 3452     |
| 6.75   | 641     | 1038     | 272     | 403      |
| 8.25   | 338     | 582      | 40      | 63       |
| 9.75   | 200     | 344      | 9.4     | 16       |
| 11.25  | 126     | 228      | 4.0     | 8.2      |
| 12.75  | 82      | 170      | 2.1     | 5.3      |
| 14.25  | 58      | 113      | 1.7     | 3.0      |
| 15.75  | 38      | 79       | 1.1     | 3.3      |
| 17.25  | 28      | 68       | 0.96    | 3.5      |
| 18.75  | 21      | 46       | 0.68    | 2.0      |
| 20.25  | 16      | 37       | 0.66    | 1.5      |
Figure 3. Full scale dose rate isolines for Molybdenum cone secondary target.

The calculated dose rate as a function of distance from the needle axis for Mo-cone secondary target was compared with experimental data. All the dose-depth profiles were measured using water-equivalent polymethyl-methacrylate (PMMA) phantoms and Harshaw LiF:Mg:Ti thermo-luminescent dosimeters (TLD-700). The experimental dose rate attenuation as a function of distance from needle axis in a PMMA phantom matched well to the Monte Carlo results as shown in figure 4.

3. Polymer gel dosimetry

Gel dosimetry is a new dosimetry technique [4]. Gel dosimeters are the first and only integrating dosimeters that enable dose verification in three dimensions. Moreover, the application of a 3D dosimetry technique in clinics can give a real push to the application of advanced high-precision radiotherapy technologies.

In polymer gels, commonly known as BANG-type or PAG-type, monomers are usually dispersed in an aqueous gel matrix. The monomers undergo a polymerization reaction as a function of absorbed dose resulting in 3D polymer gel matrix. The radiation-induced formation of polymer influences Magnetic Resonance Imaging (MRI) signal relaxation properties, optical density and other physical properties that may be used to quantify absorbed radiation dose.

Gels consist of polymer network swollen in solvent. The network of flexible long-chain molecules traps the liquid medium they are immersed in. In monomer/polymer gel dosimetry, the conversion of co-monomers to polymer aggregates upon irradiation alters the mobility of surrounding water molecules. This also results in change of spin lattice relaxation rate R1 (=1/T1) and spin-spin relaxation rate R2 (=1/T2). The dose response of R2 is more pronounced than of R1 and, therefore, can be used as an effective imaging parameter.

The BANG3™ polymer gel (MGS Research Inc.) has been used for both calibration and experimental measurements. Two phantom flasks filled with gel have been irradiated from within by
the “treatment” radiation (the fluorescent radiation produced by the Mo pseudo target). The flask 1 was irradiated for 60 minutes by an X-ray needle with a cone-shaped pseudo target, as shown in figure 5(a). The evenly irradiated area within the gel is clearly visible, as shown in figure 5(b).

![Image](image_url)

Figure 5. The gel-filled flask irradiated by a cone-shaped pseudo-target: (a) the flask with the inserted needle, (b) irradiated area of gel-filled flask (magnified image).

After irradiation, the gel-filled flasks were scanned using a 3Tesla MRI machine. The flasks were thus imaged upright on a flat lucite sheet positioned horizontally in the head-coil so that the flasks were centered in the magnetic field. Then, images were obtained at the selected depths in the flasks. Only Transverse Relaxation T2 weighted scan data (TE echo times =120, 55, 10) were used. The Longitudinal Relaxation T1 and T2* weighted scan data didn’t provide good image and, therefore, were not used. There were two options available for image slice thickness: 2mm+1mm gap or 1.5mm+0.5 mm gap. The slice thickness of 2mm+1mm gap was used for high signal to noise ratio (SNR) in the MRI images.

The R2 (R2=1/T2) map in a longitudinal slice (along the optical axis of the needle with a cone-shaped pseudo-target) was reconstructed by eigen2 software. Using the R2 map and the calibration dependence T2 vs. Dose calibration curve, the dose map was obtained by using Matlab software. The reconstructed T2 longitudinal image and the dose map of the irradiated gel (60 minutes irradiation from a cone shaped pseudo target) are shown in figure 6 (a,b). The region outlined in the small box in figure 6(a) corresponds to the area shown in figure 6(b) from the Matlab.

![Image](image_url)

Figure 6. The reconstructed T2 longitudinal image (a) and the dose map (b) of the irradiated gel (irradiation time 60 minutes; cone-shaped pseudo-target).

The R2 (R2=1/T2) map of a latitudinal slice (perpendicular to the optical axis of the needle with a cone-shaped pseudo-target) was also reconstructed by eigen2 software. Using the R2 map and the calibration dependence T2 vs. Dose calibration curve, the dose map was obtained by using Matlab.
software. The reconstructed T2 latitudinal image and the dose map of the irradiated gel (60 minutes irradiation from a cone shaped pseudo target) are shown in figure 7 (a,b). The region outlined in the small box in figure 7(a) corresponds to the area shown in figure 7(b).

Figure 7. The reconstructed T2 latitudinal image (a) and the dose map (b) of the irradiated gel (irradiation time 60 minutes; cone-shaped pseudo-target).

4. Conclusion
The basic concept of a novel needle x-ray system for medical applications is reported; the main principle of the system is based on a two-stage production of x-rays. We performed Monte Carlo calculations using Geant4 code and experimental measurements of dose rate distributions with polymer gel dosimeter in water equivalent phantoms for a range of x-ray intensities and various target design and materials of the fabricated x-ray needles. These studies have experimentally confirmed that the concept of this miniature needle based x-ray system is correct.

References
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