Three-dimensional Polymer Dosimetry

O. Ch. Turonok,1 O. V. Diachenko,1 M. Ye. Alokhina,2,3 O. A. Bezshyyko,2 L. O. Golinka-Bezshyyko,2 I. M. Kadenko,2 O. O. Chygryn3
1 Concern “Sakura,” Kyiv, Ukraine.
2 Taras Shevchenko National University of Kyiv, Faculty of Physics, Kyiv, Ukraine.
3 Cancer Center “INNOVACIA,” Lutezsh, Ukraine.

Abstract. The polymer dosimetry is a multidisciplinary experimental dosimetry method presenting the unique advantages of the 3D dose distribution mapping — dose response independence from radiation type and energy, water equivalence, arbitrary dosimeter shape and dimensions. These advantages are particularly significant for cases where steep dose gradients exist such as in intensity-modulated radiation therapy and stereotactic radiosurgery. This paper is a brief overview of the existing methods of 3D dosimetry. Special attention is paid to the polyurethane phantoms.

Introduction

Over the past couple of decades, external beam radiotherapy has evolved into a fairly accurate method for delivery of therapeutic doses of ionizing radiation to the desired area of the human body with minimizing radiation-induced side effects. One of the main tasks in radiation therapy is to spare normal tissue and to guarantee the effective death of tumor cells. The emergence of complex radiotherapy techniques has created new challenges for radiation dosimetry. Conformal radiotherapy, intensity-modulated radiation therapy, radiosurgery and brachytherapy are the methods where both spatial and quantitative accuracy is critical to the success of treatment. These complex schemes require precision in the “gray areas” of conventional dosimetry methods. Providing a map of the dose distribution in areas with a high gradient (at the edge of the beam, or about forming unit field), has always been a problem for conventional dosimetry, especially for creating a three-dimensional map of the dose distribution.

Three-dimensional dosimetry

Common and well-developed dosimeters such as the ionization chambers, the thermoluminescent dosimeters and the radiochromic films can be considered as one- and two-dimensional dosimetry systems with a limited use for spatial mapping of 3D objects. The interest in the development of 3D dosimeters of ionizing radiation was raised a long time ago. A special attention has always been given to those dosimeters, which change their optical properties proportionally to the absorbed dose. Three-dimensional gel dosimeters are based on the concept of a radiation sensitive chemical reaction of which the amount of reaction products is correlated with the total absorbed radiation dose. Three-dimensional gel dosimeters are based on the concept of a radiation sensitive chemical reaction of which the amount of reaction products is correlated with the total absorbed radiation dose. They have been studied by several research groups as early as in the 1950s [Day et al., 1951].

A study on one of the first systems based on the method of obtaining three-dimensional images dose distribution was published in the early 1960s [Potsaid et al., 1961]. This system consisted of a solid wax matrix together with a halogenated hydrocarbon as a free radical initiator and a leucobase dye. The opacity of the paraffin wax was an essential disadvantage of this dosimeter and therefore splitting of a dosimeter into parts was required to measure spectrophotometrically the concentration of the dye in each section. Over the time the quality of the image produced due to the dose deposit in the paraffin matrix decayed. The next series of innovations took place at Yale University and were associated with the use of magnetic resonance imaging (MRI) to measure the radiolytic oxidation in the Fricke gel dosimeters [Gore et al., 1984]. Then the recipe was developed for gelatin/acrylamide dosimeter BANANA [Maryanski et al., 1993] and later modified formulation named BANG (consisted of Bis, Aam, nitrogen and aqueous gelatin) [Maryanski et al., 1994]. An optical laser computerized tomographic (CT) scanner [Xu et al., 2004] OCTOPUS ™ (MGS Research Inc, Madison, CT) was used to read out the produced images. Above mentioned publication caused a huge response in the scientific community. From the end of 1990s the number of the publications on this subject was more
than a dozen a year. And fairly large number of formulations for polymer gel dosimeters was
developed (for example, BANG-3 [Maryanski et al., 1994; Maryanski et al., 1996a], MAGIC [Fong et
al., 2001], MAGAT [De Deene et al., 2002a; Hurley et al., 2005], MAGAS [Venning et al., 2005a],
PAGAT [Venning et al., 2005b], VIPAR [Pappas et al., 1999], VIPARd [Kozicki et al., 2005b],
VIPARnd [Kozicki et al., 2007; Pantelis et al., 2008], and PABIG [Kozicki and Rosiak, 2003; Pantelis
et al., 2005; Pappas et al., 2005]).

However, many of these polymeric dosimeters have significant limitations and shortcomings.
Many of these were overcome by the development of an entirely new system PRESAGE™ —
radiochromic optically transparent three-dimensional dosimeter based on polyurethane [Adamovics et
al., 2004; Adamovics et al., 2006,]. In the formulation of solid dosimeter PRESAGE™ it is a free
radical initiator and a leucobase dye. Moreover, it does not require a container to maintain its shape
(Fig. 1) [http://www.ecnurad.ugent.be/QMRI/en/research.html]. The polyurethane matrix is a tissue-
equivalent material and prevents diffusion of the dose distribution images. The dose-response of
PRESAGE is linear and independent of both the photon energy and the dose rate.

The main types of three-dimensional dosimetry

The modern three-dimensional dosimeters can be divided into three main types, namely, the
Fricke dosimeters, the polymer gels and the polyurethane radiochromic dosimeters. The first two
systems are composed of a hydrogel matrix that retains 3D spatial dose distribution in a dosimeter.

In the oxidation gels Fricke solution (acidic oxygenated aqueous iron ion (II), Fe\(^{2+}\)) is irradiated
by ionizing radiation [Schreiner, 2004]. When the solution is irradiated, the decomposition of water
causes the formation of hydroperoxide radicals (HO\(_2^+\)). Hydroperoxy radicals react with ions of iron
(II), converting it into iron ion (III) [Pikaev, 1985]. Iron ions (III) have a velocity of longitudinal
nuclear magnetic relaxation (R\(_1\)) other than water. Therefore, the dose distribution can be retrieved
from the R\(_1\) images, obtained by the MRI.

![Figure 1. The polyurethane matrix prevents diffusion of the dose distribution images.](image1)

![Figure 2. The monomer/polymer gels become visually opaque when irradiated.](image2)
The second type of the gel dosimeters is a polymer gel. The polymer gels are composed of monomers dissolved in the viscous matrix. After irradiation (Fig. 2) [http://www.iasa.gr/activities/Medical/DosLab/PolymerGel.html], the polymerization reaction causes crosslinking of monomer molecules providing a random three-dimensional crosslinked polymeric network, for example, copolymerization of acrylamide and N, N'-methylenebisacrylamide, within a gelatin matrix on the basis of water [Maryanski et al., 1993; Maryanski et al., 1994]. The degree of radiation-induced polymerization on the dose and the resulting cross-linked polymer network affects mobility of the surrounding water molecules. Thus, this results in the change of the transverse nuclear magnetic relaxation (R2). A dose card can be constructed from MRI images (R2) for the polymer. Furthermore, the applicability of the optical CT was demonstrated as an alternative to the MRI imaging [Gore et al., 1996].

Conclusions

There are numerous publications about the first two types of three-dimensional gel dosimeters — the polymer gels and the Fricke dosimeters. The underlying mechanisms and processes have been extensively investigated and are considered as well understood. Furthermore, there are numerous variations of these types of dosimeters. In contrast, there is a relatively small number of publications devoted to the polyurethane radiochromic dosimeters, and they are made mainly by group of John Adamovics. The first reports on this system appeared in 2004 and it is of undoubted commercial interest. The system consists of a polyurethane matrix, manufactured in accordance with the polyurethane technology in a two-step process, halogenated organic compounds — “free radical initiator” and leucobase triphenylmethane dye (usually malachite green). Only in a recent publication it was indicated that halogenated organic compounds are galoforms — chloroform, bromoform or iodoform. The mechanism of radiolytic processes occurring in this system in the publications by group of John Adamovics are not disclosed. However, on the basis of data, published in the Russian literature, we can assume that in the process of radiolytic oxidation of leucobase of malachite green a chain mechanism is involved with haloidmethane and oxygen participation. Usage of polyurethanes in this case is defined by the fact that this class of polymers is one of the most well-known classes of gas-permeable polymers. Thus, it can be assumed that the polyurethane radiochromic dosimeter — it’s a brand new three-dimensional dosimetry system. This direction of 3D dosimetry is still evolving. In the future these dosimeters will be used in routine clinical practice.

References

TURONOK ET AL.: THREE-DIMENSIONAL POLYMER DOSIMETRY


WWW http://www.iasa.gr/activities/Medical/DosLab/PolymerGel.html

---

61