The dose modulation transfer function concept (DMTF) in polymer dosimetry for quality control in fine photon fields

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1. Purpose

There are different methods for obtaining access to quantitative information about the spatial resolution in dosimetric imaging. For polymer dosimetry these methods have mainly been based on comparisons between the dosimetric results of film or pin-point dose visualization to those of MR-based polymer dosimetry (MRPD) the resolution being typically 1 mm. With difference we present a more systematic approach as known from general imaging concepts based on the modulation transfer concept. We investigate periodic dose modulations in photon radiation fields down to spatial structures of \( a/2 = 280 \, \mu\text{m} \) (\( a \): spatial period) using high resolution MR-microimaging at very small voxel sizes \( (V_s = 199 \times 199 \times 1000 \, \mu\text{m}^3) \). The results are compared to those of a film scanner system as used for high resolution relative dosimetry in clinical routine.

2. Introduction

The new developments in radiation therapy are mainly related to the improvement in conformity and smaller margins, demanding for 3-dimensional dosimetric methods at higher spatial resolution. Among other features the RTAP criterion [1] recommends a spatial resolution of \( 1 \times 1 \times 1 \, \text{mm}^3 \). Best results for high resolution and accuracy are reported for pin-point ionization chambers, small diodes and diamond detectors. However, these methods mostly appear to be too time consuming to verify 2- or even 3-dimensional dose distributions.

Very small voxel sizes of about \( 0.105 \times 0.105 \times 1 \, \text{mm}^3 \) have been reported for systematic investigations on the effect of pixel size on T2 [2] and highest resolution dosimetric imaging \( (V_s: 0.195 \times 0.195 \times 1 \, \text{mm}^3) \) on a gamma-knife irradiation scheme [3]. However the spatial resolution achievable in MR-based polymer dosimetry is limited by several features, represented for instance by the sensitivity of the polymerization process to dose and the sensitivity and spatial selectivity of the MR imaging device. Moreover dose images might be distorted by MR-susceptibility artefacts [4]. Therefore the resolution of polymer dosimetry is not presented by the voxel- or pixel size and must be investigated independently. In most high resolution MRPD investigations the MR-dosimetric results presented as isodose lines are compared to those of dose calculation algorithms or film dosimetry assuming the latter to be the gold standard for high resolution relative dosimetry.
With difference we present an approach based on the modulation transfer concept applied to dose imaging. The method relies on the quasi periodic modulation of the applied dose via a fine structured absorber material down to periodic structures of \( a/2 = 280 \, \mu m \). We compare the spatial dose selectivity of the microimaging device on a 3T whole body MR-system to that of a clinical film-scanner system, which has been believed to offer the best spatial resolution with comparison to other dose detection systems.

3. Subjects and Methods

3.1. The DMTF concept

We refer to the introduction of the Modulation transfer function concept (MTF) in general imaging and specifically in radiodiagnostics [5]. We extend this concept to dose imaging and assume a periodic modulation at frequency \( \nu \) in dose \( D(x) \) as object to be visualized by a dosimetric system:

\[
D(x) = D_0 \sin(2\pi \nu x) \tag{1}
\]

This modulation in signal intensity is then transferred via transfer function \( T(x-x') \) to an image: \( D_i(x') \) which exhibits a signal modulation with the same spatial frequencies:

\[
D_i(x') = D_0 \cdot \text{DMTF} \sin(2\pi \nu x' - \phi) \tag{2}
\]

The dose modulation transfer function \( \text{DMTF}(\nu) \) is described by the Fourier transform of the Transfer function: 

\[
\text{DMTF}(\nu) = \left[ \left( \int T(x) \sin(2\pi \nu x) \, dx \right)^2 + \left( \int T(x) \cos(2\pi \nu x) \, dx \right)^2 \right]^{1/2}
\]

Consequently the Fourier components of the dose image are related to those of the actual dose distribution via the DMTF-function, which actually gives the ratio of the Fourier components. In most imaging systems the low spatial frequencies of the object are correctly visualized in the image, which is equivalent to a MTF-function of 1. However, if the spatial structures are getting smaller towards the limits of spatial resolution of the imaging system, the DMTF will drop with higher frequencies. The extent of the reduction in the modulation depth represents a measure of the spatial resolution of the system.

3.2. Experimental realization of the dose modulation

The modulation in dose was achieved by an absorption grid of brass, in which fine quasi-periodic structures of sizes between about 280 \( \mu m \) (525 \( \mu m \)) and 1125 \( \mu m \) were sawed. The grid was \( \gamma \)-irradiated by means of a \( ^{60} \text{Co} \) external treatment unit (gamma: 1.25 MeV, Theratron) with first an underlying gel sample and second a dose sensitive film for therapy verification (Kodak X-omat). The dose response of the film could be obtained after calibration of the optical density by a set of \( ^{60} \text{Co} \) irradiations between 100 and 2000 mGy. An optical scanner (Densitometer: FIPSPLUS, PTW, Freiburg, Germany) for dose verification adjusted for finest pixel size (200 \( \mu m \)) was used for obtaining intensity profiles across the modulations of optical density.

The polymer gel samples, kept in small glass tubes (i.d. = 20 mm), mainly consist of acrylic monomers in a gel matrix. In this work we investigated BANG\textsuperscript{®} gel (item code: VIAL, MGS Research; Guilford, Conn., USA) [6]. The dose response (Leksell Gamma Knife, Elekta Instr., Stockholm, Sweden) of the polymer gels was investigated for calibration from 1 to 20 Gy at increments of about 2.5 Gy (\( ^{60} \text{Co} \)). High linearity, important for relative dosimetry, as performed here, was obtained in this regime (\( R^2 = 0.98 \)). High spatial resolution is achieved on a high field (3T) whole
body MR scanner (Medspec 30/80, Ettlingen, Bruker Biospin, Germany) using an additional strong gradient system \( G_{\text{max}} = 200 \text{ mT/m} \) insert and a small r.f. resonator \( d_1 = 3.5 \text{ cm} \) as detection unit. A CPMG pulse sequence with twenty equally spaced echoes between 20 and 400 ms has been applied for T2 calculation in each pixel element \( \text{FOV} \ 2.55 \times 2.55 \text{ cm}^2; \text{MTX}: 128 \times 128; \text{slth}: \ 1000 \ \mu\text{m}; \text{Nav}: 32 \). The T2 maps are transferred to dose images using the calibration results.

4. Results

A high-resolution T2-image is obtained for the modulated dose irradiation scheme (figure 1).

![Figure 1](image1.png)

**Figure 1.** T2-image of the polymer gel. The modulation in T2 is due to the dose modulation of the grid absorber. Also the finest two slits at right \( a = 560 \ \mu\text{m} \) can be seen. The position of the dose profile (figure 2) is indicated.

![Figure 2](image2.png)

**Figure 2.** Dose profile calculated from the T2-image along the line indicated in figure 1. The highest peaks at left belong to the modulation period of 2250 µm. This modulation depth is set to 100%. The finest modulation at right (arrow) refers to the period of \( a = 560 \ \mu\text{m} \). The corresponding modulation amounts to 29%.

Dose images are calculated using the calibration results. One profile (see figure 2) at width of 1 pixel is selected avoiding the partial volume effect of neighbouring pixels \( 199 \ \mu\text{m} \) positioned just between solid brass finger and the neighbouring slit. The modulation depths for obtaining the DMTF are derived from the dose profile and related to the modulation of highest depth \( \Delta D_{\text{max}} = 1,62 \text{ Gy} \) referring to the periodic structure of \( a = 2250 \ \mu\text{m} \). The results for the other spatial frequencies are presented in table 1.

For comparison, the results of densitometric scanning of the Kodak film are shown in figure 3. A dose profile (see figure 4) is calculated from film calibration data.
Figure 3. Densitometer scanned film (nominal pixel size: 200 µm). Dark regions refer to high dose levels under slits of the brass grid. The black stripe indicates the position of the profile (figure 4). The finest two slits ($a/2 = 280$ µm) at right can hardly be separated.

Figure 4. Dose profiles, calculated from the profiles of the optical density (figure 3). The finest two slits ($a = 560$ µm) correspond to the two small maxima at right. The modulation depth is reduced to about 11% of the maximum modulation ($a=2250$ µm) at left.

Though on film the modulation in optical density at all structural widths could be observed clearly the finest dose modulation at $a/2=280$ µm could hardly be resolved due to the limited, nevertheless highest available, scan resolution of the scanner (see also table1 for dose modulation depth).

Table 1. Dose modulation depth for different spatial frequencies $\nu =1/a$. The relative decrease of the detected dose modulation depth with higher spatial frequency for (a) MR-gel dosimetry, and (b) the film-scanner systems represents a measure of the spatial resolution of the corresponding dosimetric imaging system.

| Dose modulation $D = D_{\text{min}}/D_{\text{max}}(\nu)$ | $\nu=1/(2250$ µm) | $\nu=1/(1050$ µm) | $\nu=1/(560$ µm) |
|---|---|---|---|
| (1) Dosimetry by a film scanner system | 100 % | 45 % | 11 % |
| (2) Polymer gel dosimetry: MRPD | 100% | 53% | 29% |

5. Conclusion

The DMTF concept is proposed for quantitative comparisons of the spatial resolution in MR-based polymer dosimetry with reference to other dosimetric imaging methods. Though the experimental implementation of defined dose modulations below 1 mm remains difficult, it has been shown that MR-based gel dosimetry is capable of detecting such fine dose modulations. By separating dose differences at 280 µm distance it may be even a competitor to clinical film-scanner systems. However the requirements for MR-gradient-hardware and sensitivity of the detector are quite demanding for such high spatial resolutions and may limit clinical use.

Acknowledgements

This contribution was supported by funds of the mayor of Vienna (Grant No. H-194-99) and the Austrian National Bank (OENB Nr.10229/2003).
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