Dosimetric performances of optically detected Fricke-agarose-Xylenol Orange gel

A. M. Luciani^{ab}, A. Palma^{ab}, S. Grande^{ab}, P. Sordi^{a}, L. Guidoni^{ab}, V. Viti^{ab}, E. Di Castro^{c}, C. De Felice^{c}, A. Lo Bosco^{c}

^{a}Dipartimento Tecnologie e Salute, Istituto Superiore di Sanità and ^{b}INFN Gruppo Collegato Sanità, Viale Regina Elena 299, 00161, Roma (Italy)

^{c}Istituto di Radiologia, Fisica Sanitaria Policlinico Umberto I, Università “La Sapienza” Roma

Corresponding author’s e-mail: guidoni@iss.it

Abstract. A first prototype of optical scanner based on a CCD camera and the use of Fricke-agarose-XO has allowed us to reconstruct 3D dose maps, monitoring doses in the range 0.5-3 Gy. Measurements performed with laboratory tests and with clinical beams would indicate that the uncertainty involved in dose mapping are compatible with requirements of a 3D dosimetry for the verifications of treatment plans.

1. Introduction
In the field of gel dosimetry, we are examining Fricke-agarose-Xylenol Orange (XO) gels for obtaining 3D dose maps. This kind of gels have the advantage of a simple and inexpensive preparation. Addition of the dye XO complexing the oxidized metal ions in Fricke-gel systems provides the opportunity to measure the dosimeter absorbance in the range of visible light, enhancing both sensitivity and specificity of the optical analysis. The main drawback of the system, that is ion diffusion after irradiation can be overcome by the use of optical techniques particularly by utilizing a CCD for detection, due to very quick acquisitions of 2D projections. The presence of XO in the gel further reduces ferric ion diffusion.

A first prototype of optical scanner based on a CCD and the use of Fricke-agarose-XO has allowed us to reconstruct 3D dose maps, monitoring doses in the range 0.5-3 Gy. Laboratory tests and measurements with clinical beams were then performed.

2. Preparation and measurements details.
Optical readings were made at measurements of the radio-chromic Fricke-agarose-Xylenol Orange gel. Optical differences \( \Delta OD \) of samples before and after irradiation were measured. For this purpose, a CCD based optical scanner was used. Details on the dosimeter preparation and on optical measurements are here reported.

2.1. Choice of the wavelength
To exploit the formation of a coloured complex between the dye Xylenol Orange (XO) and ferric ions, it was necessary to take into consideration characteristics of the complex and optimum wavelength readings, that were the subject of many studies. In particular detailed studies [1] have shown that, for determination of unknown amounts of ferric ions, it is not convenient to read the solution at the peak absorbance, near 543 nm, because in that spectral region a relevant contribution of free dye is also present. A correction for this contribution is possible, but strongly dependent on the extinction coefficient of both components, that may change due to differences in pH and to the impurities often present in the dye, depending on dye source. It is therefore suggested to read the Optical Density (OD) at 560 nm, in order to minimize the contribution of free XO. At this frequency, the absorption of the free dye is very low. According to the study reported in [1], the estimated error at 560 nm is 1.6% in a solution of 25 mM H$_2$SO$_4$, 25 mM Fe$^{3+}$, 125 mM XO. The light box of our scanner was set for emitting monochromatic light at 567 nm. The choice of 567 nm further decreases this error, with negligible effect on gel sensitivity.

2.2. Binning of data
To increase signal to noise, we used the binning procedure. Binning is a process of combining the charges in adjacent pixels on the CCD, prior to readout, which effectively increases the size of the pixel. The net result is a charge that is the sum of the charges of the binned pixels which yields an improved signal-to-noise ratio. Binning quantities are user-set in any aspect—for example 2 x 2, 4 x 4, 1 x 100, etc. We have considered 3x3, 6x6 and 11x11 pixels.

2.3. Dosimeter composition (2D Projections)
For accurate measurements, the absorbance of the complex must be independent by the relative concentration of XO. This condition is satisfied when concentration of XO is at least three times that of ferric ion. According to reference [1], a ratio of 5 gives safer margins.

2D measurements were then performed, by examining 2D projections, in order to control the performance as far as composition and stability are concerned for the dosimeter gel. Sucrose was included in gel formulation and the resulting dosimeters were compared. The presence of sucrose, keeping the agarose molecules apart, is intended to avoid the formation of lumps, allowing to obtain a very homogeneous gel with a consequent small uncertainty of pixel values. Figure 1 shows the distribution of ΔOD values for a 6x6 pixel of gel without (left) and with (right) sucrose in a region of interest (ROI) of homogeneously irradiates gels. In Table 1, comparison of the performances of gels

![Figure 1. Distributions of the optical difference values (ODdiff) for a 2D projection (binning 6x6 pixel) for irradiated gels without and with addition of sucrose for a homogeneous irradiation with 1 Gy.](image)
with (Gel II) and without sucrose (gel I) is shown for two irradiation doses and by binning data with different pixel sizes. Mean values and percent standard deviation are reported.

From the present results we may infer:

- percent standard deviation is always lower in gel containing sucrose; this should be a consequence of a more uniform gel preparation.
- sensitivity is higher for gel containing sucrose.

Table 1. ΔOD mean values ΔODm and percent standard deviation from gel without and with sucrose, homogenously irradiated with a $^{137}$Cs source at two different doses and binning data with different numbers of pixels.

| Binning | No sucrose | | Sucrose | |
|---|---|---|---|---|
| | $\Delta$ODm | % st dev | $\Delta$ODm | % st dev |
| 1 Gy | | | | |
| 3x3 | 0.068 | 3.07 | 0.095 | 1.3 |
| 6x6 | 0.068 | 2.43 | 0.096 | 1.0 |
| 11x11 | 0.068 | 2.05 | 0.095 | 1.1 |
| 3 Gy | | | | |
| 3x3 | 0.18 | 1.41 | 0.29 | 1.2 |
| 6x6 | 0.18 | 1.21 | 0.09 | 1.1 |
| 11x11 | 0.18 | 1.14 | 0.29 | 1.2 |

From data reported in Table 1, it is possible also to observe the reduction in the percent standard deviation by increasing numbers of pixels for data binning.

2.4. Differences in gel preparations
Performance of different gel preparations with the same composition was then studied. Gel stability as a function of time was checked showing that the optical density of the gel samples was stable from 24 hr up to 32 hr after the gel preparation for both control and irradiated samples keeping the gel in the temperature range 22-25 °C.

Comparison between four samples deriving from preparations of different days were then compared, by taking measurements from two samples from the same preparation (a and b). Parameters obtained by linear fitting the dose response curve with the equation $\Delta$OD=$m$*Dose, in the range 0-4 Gy, are shown in Table 2. These data show that the same preparation had very close parameters, while larger differences were observed in different days. Consequently, this kind of dosimeter can be used only for relative dosimetry.

Table 2. Parameters of linear fitting of dose response curves for samples from the same preparation (cuvette a and b) and from different preparations (marked with the number of the experiment).

| N. Exp | $m_a$ | SE_a | $R^2_a$ | $m_b$ | SE_b | $R^2_b$ | $\frac{(m_a-m_b)}{\sqrt{(SE_a)^2+(SE_b)^2}}$ |
|---|---|---|---|---|---|---|---|
| 1 | 0.096 | 0.001 | 0.9997 | 0.097 | 0.001 | 0.9996 | 0.9 |
| 2 | 0.091 | 0.004 | 0.9998 | 0.091 | 0.003 | 0.9994 | 0.03 |
| 3 | 0.097 | 0.001 | 0.99 | 0.099 | 0.001 | 0.9998 | 1.6 |
| 4 | 0.102 | 0.001 | 0.9991 | 0.1091 | 0.0005 | 0.9986 | 0.1 |
3. 3D dose maps

The gel was irradiated in a cylinder 0.7 cm (r) x 10 cm (h). 180 2D projections were obtained by rotating the sample and then 3D dose maps were obtained by means of an ad hoc software based on a back projection algorithm.

Results from two irradiation sections are here presented. The first one was relative to a laboratory test performed by irradiating the sample in a $^{60}$Co cell where a dose gradient was obtained by shielding part of the sample during irradiation. The second one was relative to an irradiation with clinical beams of a Linear Accelerator (LA) of 6 MV.

3.1. Laboratory tests

Uncertainty of pixel values is the main source of uncertainty for dose measurements. To evaluate this uncertainty, the gel containing cylinder was irradiated in a $^{60}$Co cell with a dose of 10 Gy and by shielding part of the gel. TLD dosimetry was used for calibration. With this arrangement, dose was homogeneous within approximately 2 % in the axial direction, that is perpendicular to the longitudinal axis where the dose gradient was obtained. Figure 2 shows the percent standard deviation of the optical density difference in 10 mm raws, with a spatial resolution of 0.51 cm$^3$, as a function of the dose. It is possible to observe that, with this spatial resolution, percent standard deviation exceeded 2 % only in the lowest dose range.

![Graph showing percent standard deviation vs dose](image)

Figure 2- Percent standard deviation of the optical density in a 10 mm raw with a spatial resolution for voxels of 0.51 cm$^3$, as a function of the dose.

3.2. Dose maps with clinical beams

Irradiation of the gel containing vessel set in a polystyrene phantom was performed with a LA at 6 MV, as shown in Figure 3a. The irradiation field was 10x10, with 3 Gy to the isocenter. Doses were measured with an ionization chamber I.C. (0.13 cc) to give the profile in water phantom. Its accuracy was 1.9%. Absolute dose measurement was performed in polystyrene phantom with a I.C. of 0.6 cc. Figure 3b shows one longitudinal section from the reconstructed 3D map obtained from the 2D projections through the software for the 3D reconstruction.
Figure 3. a) Geometry of irradiation of the Fricke-gel dosimeter in the polystyrene phantom with the 6 MV LA; b) a longitudinal section from the reconstructed 3D map.

Figure 4. Comparison between dose values obtained with the I.C. and the gel (longitudinal column) with a spatial resolution 1mm³.

Comparison between relative doses measured with I.C. and that measured with Fricke-gel is shown in Figure 4. These data show that in the plateau region with a 1mm³ spatial resolution the standard deviation in this gel dosimeter was 0,045822, that is 1.5%.

4. Conclusions
Measurements performed with laboratory tests and with clinical beams would indicate that the uncertainty involved in dose mapping are compatible with requirements for a 3D dosimetry for the verifications of treatment plans.

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References
[1] Gay C, Collins J, Gebicki M. Determination of iron in solutions with the Ferric-Xylenol Orange complex. Anal. Biochem. 273, 143-148 (1999).